BACK AND BED
Ergonomic Aspects of Sleeping

Bart Haex

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Ergonomic Aspects of Sleeping
Preface

The book behind this preface does not have the pretension to be the final work on the ergonomics of sleeping. It rather hopes to initiate a dialogue on this important issue. Given that most participants in this dialogue are still unknown at present, some readers may find the book too complex, while others would probably like it to be even more profound. Future will tell, but in the meantime, I wish all readers a very good sleep.

Writing this work would not have been possible without the help of many others. I am therefore very grateful to the people who reviewed this book: R.Holvoet, Prof. R.Van Audekercke, Prof. G.Van der Perre, Prof. J.Vander Sloten, Prof. R.Gobin, Prof. G.De Roeck, Prof. Ph.Lauweryns, and Prof. E. Hierholzer.

Furthermore, it builds on contributions by H.Haex, R.Van Haute, J.Baeteman, T.Huysmans, F.Kermis, S.Notelaers, B.Saye, P.Oris, M.Gilio, M.Reynders, T.De Wilde, B.Porteman, D.De Blauw, B.Degraeuwe, R.Motmans, W.De Craecker, G.Janssens, and the input of many others. I could also invariably rely on an even larger group of people—among these my former and present colleagues at the Division of Biomechanics and Engineering Design—for temporarily lending themselves for sleeping tests.

Last but not least, I’d like to thank my family, in particular my young son Matthias, who is the living proof that sleeping is an absolutely essential part of life.

Bart Haex
Introduction

Aim

We spend approximately one third of our life in bed, while a synergy of psychological, physiological, and physical conditions affects the quality of sleep. Due to an insufficiently adapted sleep system (i.e., mattress+support structure+head cushion) or an incorrect sleeping posture, the human body—especially the vertebrae—is often supported unsatisfactorily, causing low back pain—one of the most compelling problems in the industrialized world—or sleep disorders in general. Although many things have been said and written about this issue, it is disturbing to find how few of these communications are founded on actual research, especially those statements that are made to the general public through different media, mostly for promotional purposes.

Consequently, a strong demand for brightening up this twilight zone is expressed by both development and marketing units, and—not to underestimate—by the public at large. This study therefore aims at creating a scientific foundation for further research. It has, however, neither the intention nor the pretension to bring the complete mutual relationship between physical factors and the mental quality of sleep to light. It rather concentrates on the effects of environmental factors, leaving the unfolding of sleep psychology as a subject on its own.

Given that sleep is often considered as a black box, without looking for the underlying determinants and relationships, this book aims at opening the box by defining and combining several aspects of sleep and by identifying characterizing parameters for each of these aspects. This method might seem to be ambitious, but it is the only sound way to establish a scientific long-term basis for further research.

Guidelines

In view of the diversity of the readers of this book, it is probably sensible to define several levels of complexity. The basic level (Level 1 in Figure 0.1) explains which ergonomic factors (e.g., back support) play a role in sleeping (Chapter 1), and recommendations are given accordingly (Chapter 6). On a medium level (Level 2 in Figure 0.1), the underlying determinants of the
cited ergonomic factors (e.g., the influence of posture on back support during sleep) are uncovered (Chapter 2), and the research behind the recommendations (e.g., why different people need different beds) is explained. On a top level (Level 3 in Figure 0.1), different measuring techniques (Chapter 3) and modeling procedures (Chapter 4) are described.

The basic level is intended for everyone, even though terminology might be complicated at times. The medium level is intended for people with an ergonomic background (e.g., engineering, medicine, physical therapy) and for those who want to know more about the underlying research. The top level is intended for sleep professionals who are actively involved in sleep research or bed design, which does not imply at all that these chapters would be uninteresting for laypeople.

Overview

The first chapter (“Which Ergonomic Factors Affect the Quality of Sleep?”) defines the basic ergonomic principles of sleeping by accumulating available data. Physical, physiological, and psychological factors affecting the quality of sleep are discussed, as well as cultural diversity and historical evolution with respect to this issue.

The second chapter (“Bed Type Variety—Sleeping Posture Diversity”) explains how different types of body support and different postures influence the physical factors cited in the first chapter, while the most important and therefore most stressed component is the sleep system itself. Different materials and their influence on the quality of sleep are discussed.

Chapter 3 (“How to Measure Spinal Alignment”) and Chapter 4 (“Spinal Alignment: Computer Simulations”) meet the need for an objective and scientifically sound method to determine the right sleep system for each individual, based on spinal alignment. Experiments, both virtual and actual, are meant to evaluate the spine during bed rest by comparing the spine position on a sleep system with the spine position during upright standing. Different measurement techniques are analyzed and compared. Furthermore, how measurements can be modeled or simulated in order to reduce—or even avoid—the
elaborate procedures associated with actual measurements is discussed. The main advantage of simulations is the fact that the number of measurements decreases considerably. New concepts of sleep system design can also be evaluated without actually building them.

The fifth chapter (“The Impact of Custom-Made Bed Design on Back Support”) discusses the experiments that were carried out, and how these measurements provide a clear insight into the impact of bed design on spine support—especially in relation to anthropometrical properties. Starting from guidelines generated by simplified measurements, the influence of different types of body support on spine support is studied in depth through detailed measurements, while gradually focusing on the relation with anthropometrical properties. People are subdivided into several population classes in order to allocate a suboptimal but feasible solution for every subject.

In the sixth and final chapter (“Guidance to the Optimal Bed”), recommendations are made based on this knowledge, both for healthy people and people with low back pain. Furthermore, it is explained how these guidelines can be a basis for applications in a research environment (e.g., for ergonomic specialists designing sleep systems) or for end users (e.g., by providing a comprehensible Web-based client advice system).
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*Which Ergonomic Factors Affect the Quality of Sleep?*

A combined action of physical, physiological, and psychological conditions affects the mental and physical quality of our sleep. These conditions should, however, not be considered apart from each other, since physical factors can easily influence the mental quality of sleep and vice versa. Furthermore, physiological reactions of the human body are often a response to the physical condition of the body in its environment. As a result, many of the different aspects of sleeping that are described in this chapter are closely related to each other.

The first section of this chapter gives an overview of the most important ergonomic factors affecting the quality of sleep. The focus will, however, lie on physical factors, such as the mechanical properties of a mattress. At a later stage, the underlying determinants of these ergonomic properties will be discussed, including the influence of different types of body support and different postures (see Chapter 2).

The most important and therefore most emphasized environmental component is the sleep system (i.e., mattress+support structure+head cushion) we are “lying and relying” on. It mainly affects our physical condition during the night and, consequently, during the day. A proper sleep system has to fulfill many needs, depending on personal requirements, and has to be appropriate for different sleeping postures. Most authors consider a resting place being economically justified when the entire musculoskeletal system is able to recuperate well: muscles have to relax while the unloaded intervertebral disks are rehydrating. Due to an insufficiently adapted sleep system or an incorrect sleeping posture the human body, especially the vertebral column, is often supported unsatisfactorily, involving low back pain—one of the most compelling problems in the industrialized world (Hildebrandt, 1995)—or sleeping disorders in general. Despite a growing consciousness of back problems, this is still the case for many chairs, couches, and beds that are available on the market. The physical properties of a sleep system, which largely determine its support qualities, will therefore be discussed in detail.

Next to these physical factors, which are for the larger part external factors situated “outside” the human body, the physiological reaction of the human body to this physical environment has a considerable influence on the quality of sleep. Despite this apparent link, physiological reactions are often considered to be “subjective,” possibly because they are often difficult to quantify or to objectify due to the lack of appropriate measurement equipment. They should, however, not be overlooked when advising an appropriate sleeping environment to an individual; next to a house dust mite or latex allergy, other limiting constituents—like respiratory problems or excessive sweating—make it virtually impossible to ignore these physiological reactions. These issues are described in the second section of this chapter. Also, psychological factors, such as the
associations the mind makes before going to sleep, will be discussed in brief (see Section 1.3).

Finally, an optimal sleeping environment has to be chosen by assigning different weight factors to these qualities, depending on the objectives that have to be fulfilled for an individual. This choice does not only depend on individual characteristics, but also on cultural differences between population groups. One must also keep in mind that most of these factors do not withstand the pressure of time: sleep habits evolve from generation to generation, as do the mechanical properties of a mattress (even a fatigue-resistant mattress will lose 10 to 15% of its elasticity after 10 years). The fourth section of this chapter stresses the cultural differences and history-dependent aspects of sleeping.

1.1 Physical Factors

When concentrating on the development of sleep systems for the prevention of back problems, mechanical properties (especially back-support qualities) are more significant than nonmechanical characteristics (e.g., heat transport), which implies that mechanical properties (e.g., mattress elasticity) need to be optimized within the limitations posed by nonmechanical preconditions (e.g., high perspiration of an individual). Within mechanical objectives, back-support qualities are considered to be primary, keeping in mind that peak values for other parameters (e.g., pressure peaks) should be avoided. Only in cases involving applications injured people, other issues come first: pressure-relieving qualities become of prime importance in case of hospital applications. When concentrating on the development of sleep systems in general, mechanical properties should be optimized within the limitations posed by nonmechanical preconditions.

At first sight, material properties of a sleep system seem to be a question of personal preference. In reality, they should be adjusted to personal needs in an objective way, because they are the underlying determinants of most physical ergonomic features (e.g., spine support). Heavier persons, for example, need a firmer mattress in order to prevent the pelvic girdle from sinking too deep into the mattress. Materials therefore have to be developed and combined in order to optimize general sleep system characteristics. Standardized tests are able to describe the most relevant properties: mattress elasticity, hysteresis, and density. These material properties determine several physical targets: material elasticity should guarantee a correct support of the human body, hysteresis should be minimized to avoid exaggerated energy consumption while moving, and material density mainly affects fatigue resistance of the mattress itself. The physical targets are described first in this chapter; the underlying properties will be illustrated in detail later (see Chapter 2).

1.1.1 Spine Support

It is justified to consider back injury as a social problem; only a few people (20%) are never confronted with it. Low back pain is often caused by overloading the spinal column (Hayne 1984), for example, by carrying heavy loads, by making brusque movements (Mannion et al. 2000), or by adopting an incorrect posture for a long time. Although prolonged bed rest should be avoided (Ernst 1991), natural sleep may have a healing
effect on low back pain (Beaumont and Paice 1992). If the spinal column is unloaded during the night and if it is supported in its natural, physiological shape, it should be able to recuperate from daily activities. Therefore, it is important that every person sleep on an adequate combination of a mattress, a mattress support, and a pillow (Idzikowski 1999). Since both body dimensions and body weight distribution have an important influence on the position of the vertebral column on a sleep system, every person should have an individually adapted sleep system. In practice such is not possible. People will therefore be subdivided into population classes, which will be discussed later (see Chapter 5).

1.1.1.1 Anatomy of the Spine

This paragraph briefly discusses the most relevant terminology and spinal anatomy that are used later in this work. First, commonly used body planes and axes are defined: Figure 1.1a illustrates the sagittal plane (1) and the medial sagittal plane (2) subdividing the human body in two equal partitions. Figure 1.1b marks the transverse plane (3), and Figure 1.1c defines the frontal (4) plane. Sagittal (5), transverse (6), and longitudinal axes (7) are marked. Further, anterior alludes to the front side of the human body, posterior to the opposite side; proximal denotes close to the head and distal at a greater distance from it; medial denotes close to the medial sagittal plane and lateral at a greater distance from it.

The musculoskeletal system of the trunk (illustrated in Figure 1.2) consists of soft tissue (muscles, ligaments, intestines, etc.) and hard tissue, namely

FIGURE 1.1 Commonly used body planes and axes.
the vertebral column (1), the rib cage (2), and the pelvis (3). The vertebral column has the
difficult task to give the trunk both rigidity and mobility and is, therefore, its most
vulnerable part. The rib cage and the pelvis produce higher trunk rigidity. The rib cage
consists of 12 pairs of ribs, as shown in Figure 1.2 in a lateral and posterior view. Each
rib is connected to a thoracic vertebra by a hinge joint and to the sternum by a flexible
cartilage bone joint, enabling rib motion.

The vertebral column (columna vertebralis) consists of 24 rigid vertebrae separated by
soft intervertebral disks (disci intervertebrales). Figure 1.3 illustrates the vertebral column
in two different views. The cervical vertebrae are small and support the head; the upper
two have a slightly different shape to permit movements of the head. The thoracic
vertebrae or trunk vertebrae are connected to the rib cage. The lumbar vertebrae are
rather large since body
weight and motion heavily load them. The sacrum consists of five merged vertebrae and the coccyx. The sacrum is connected to the pelvis by two sacroiliac joints.

The vertebral column has a physiological curvature to intercept the shocks produced by body motion and to enable the vertebrae to support the weight of the upper body. In a sagittal projection a normal vertebral column has four bends (Figure 1.3): a forward neck curvature (cervical lordosis (1)), a backward thoracic curvature (thoracic kyphosis (2)), a forward waist curvature (lumbar lordosis (3)), and a backward sacral curvature (sacral kyphosis (4)). The lumbar part of the vertebral column always moves together with the pelvis, since the most distal lumbar vertebra (L5) is connected to it.

The hard tissue of an individual vertebra (see Figure 1.4) consists of a vertebral body or corpus at the anterior side (1), a vertebral arch in the middle (2) and a spinal process, facet joints, and transversal processes at the posterior side (3). The spinal process (processus spinosus) is the largest process on the vertebral arch and is oriented backward (4). The transversal processes (5) are oriented perpendicularly to the presented view. The four remaining processes on the vertebral arch are connected to corresponding processes on the upper and underlying vertebra: they form so-called facet joints (6) enabling a controlled vertebral motion.

Facet joints are kept together by a capsule and ligaments (1) being part of the vertebral soft tissue as illustrated in Figure 1.5. Further, every vertebra has an aperture in between its vertebral body and its vertebral arch. When
FIGURE 1.5 Sagittal cross section of two lumbar vertebrae.

vertebrae are placed on top of each other, the combination of all of these openings constitutes a bony tunnel: the vertebral canal (2). In this canal the spinal cord—the vulnerable connection to the brain—is situated.

Between two vertebral bodies, an intervertebral disk (discus intervertebralis) is situated, functioning as a shock damper and contributing to the stability and mobility of the vertebral column. By exception there is no intervertebral disk situated in between the first and the second cervical vertebra. The most important forces damped by the intervertebral disk are those acting on the back during daily activities: walking, running, jumping, etc. On the outside, it is composed of layers of concentric fibers consisting of tough tissue, being the annulus fibrosus (3). These fibers surround a jelly core, being the nucleus pulposus (4). The annulus fibrosus absorbs the shocks, which the intervertebral disk is exposed to, by enduring tensile forces, pressure, and shear forces. The intervertebral disk is connected to the vertebra by a cartilaginous cover (5) at the end plates of the vertebral bodies.

Water constitutes 80 to 85% of an intervertebral disk. When loading the vertebral column, part of the fluid of the intervertebral disk will be lost. Due to annulus dehydration, an intervertebral disk will lose between 6 and 13% of its core fluid when body weight is loading the vertebral column for four hours. In a horizontal position—as is the case during sleep—the intervertebral disks are unloaded and are able to recuperate fluid (rehydrate). This effect causes human beings to elongate approximately 1 cm during sleep.

Ligaments obstruct extreme movements, stabilize the vertebral column, and protect the underlying structures. At the anterior side, all vertebral bodies are connected over the entire length of the vertebral column by a wide and very strong ligament, the ligamentum longitudinale anterius (6), which protects the column against extreme backward movements. The ligament is connected to the intervertebral disks and the middle part of the vertebral bodies. At the posterior side of the vertebral bodies, a narrow and less strong ligament, the ligamentum longitudinale posterius (7), connects both the intervertebral disks and the vertebral bodies, forming the anterior surface of the spinal cord. Finally, ligaments connect the vertebral arches of successive vertebra (8), the processi spinosi of successive vertebra (9), and the processi spinosi over the entire length of the vertebral column (10). All ligaments are strongly innervated and therefore can be the cause of (non-) local pain.
All vertebrae, connected by ligaments, constitute a flexible vertebral column. This column is, however, not able to preserve any trunk position by itself. Trunk muscles—both back and abdomen muscles—add an important and necessary stabilizing factor to the flexible vertebral column. Back muscles control the trunk movement and consist of (a) short muscles connecting one vertebra to another and (b) long muscles spanning a large part of the vertebral column. Abdomen muscles are connected to the rib cage; when they are well developed, their tonus is able to realize a higher intra-abdominal hydrostatic pressure, and to partly unload the vertebral column.

Finally, the rib cage and the pelvis also produce higher trunk rigidity. The sacrum is connected to the pelvis by two sacroiliac joints. As mentioned earlier, the lumbar part of the vertebral column always moves together with the pelvis, since the most distal lumbar vertebra is connected to it.

### 1.1.1.2 Back Pain

Virtually everybody is confronted at least once in his or her life with back pain, making it one of the most compelling problems of the industrialized world. Most complaints can be categorized as functional—because of the mechanical origin—and refer to the lumbar area, which is exposed to pressure and tension forces mounting under the load of body weight and movements. According to Nachemson (Nachemson and Elfstrom 1970), intervertebral disks function as a shock absorber, and the vertebral column is typically overloaded by maintaining a harmful posture (as illustrated in Figure 1.6), by repeating fatiguing movements (Dolan and Adams 1998), or by carrying out daily activities improperly, thus causing or aggravating this

![FIGURE 1.6 Lumbar intervertebral disk pressure relative to upright position.](image)
particular kind of low back pain. Also, ligaments and joints can be damaged by this overload.

In a horizontal position—as is the case during sleep—the intervertebral disks should be unloaded and be able to rehydrate in order to regain their elasticity (Adams and Hutton 1983). Further, the lower pressure enables the cartilage in the facet joints to recover, and muscle relaxation can be obtained on a well-conditioned sleep system on which mobility and stability are promoted (see Section 1.1.3). Intervertebral disk injuries and the way they act on the surrounding soft tissues are responsible for the main part of posture-dependent low back pain. Facet joint or ligamentous impairments are of rather secondary importance. As detrimental postures can be produced by an insufficiently adapted sleep system or an incorrect sleeping posture, the vertebral column should be unloaded as much as possible, also during the night.

The optimal sleep system for normal healthy people—as most ergonomic specialists (Gracovetsky and Farfan 1986, Oliver and Middleditch 1991, Pheasant 1991) suggest—has to support the human spine so as to optimize load distribution in order to minimize stress. A semi-Fowler’s position with bent knees (135°) and hip joints (45°)—resulting in a relaxed iliopsoas muscle (i.e., the great flexor muscle of the hip joint, divisible into two parts, the iliac and great psoas) and a slightly smoothed lumbar lordosis—approximates the unloaded posture experienced by astronauts. Due to the impossibility to measure this ideal position, most authors take the spinal curvatures in the upright position as reference, while others suggest that the lumbar lordosis is to be flattened (Dolan et al. 1988). The reference position practiced throughout this work gives the spinal column the same thoracic kyphosis and lumbar lordosis as in the upright position, yet slightly smoothed by the fact that, in a sleep position, the direction of the gravitation vector no longer coincides

**FIGURE 1.7** Optimal support of the spine in a lateral position.

with the cranio-caudal direction of the body; a prolongation of the spine of 2% (Krag et al. 1990) and a consequent smoothening (Tyrrell et al. 1985)—as during weightlessness (Krag et al. 1990, LeBlanc et al. 1994, Wing et al. 1991)—is applied to the reference. For a lateral posture, an optimal support gives rise to the spinal column being a straight line when projected in a frontal plane (see Figure 1.7) in order to achieve a symmetrical loading of the spine (Gracovetsky and Farfan 1986). The incapability of the human body to control the spinal column actively when sleeping justifies the definition of a correct sleep system for each individual, by defining and combining different materials correctly.

When a sleep system is too soft, places where body weight is concentrated (e.g., the hip zone) will sag into the mattress. Some muscles may relax well in this position, but the
spine certainly will not; when lying in a supine position, the pelvis will cant backward, resulting in an excessive and unnatural smoothening of the lumbar lordosis. At the anterior side, intervertebral disks will be compressed while soft tissues (e.g., ligaments) will be under tension at the posterior side. When sleeping in a lateral position, the spine will be loaded asymmetrically, as shown in Figure 1.8. Most mattresses that are worn down have the characteristic to sag in the middle part; a typical solution is to put a stiff wood board under the mattress, which insufficiently corrects the support properties and may cause ventilation problems (see Section 2.1.2.4.2).

When sleeping on too firm a mattress the spinal column is supported incorrectly; in the case of a lateral position, only places with a large body width—the shoulders and the hip zone—will be supported, as can be seen in Figure 1.9. The lumbar region will bend down, especially in people who have a more pronounced contour (e.g., women). In a supine position the pelvis cants forward under the influence of tension in the musculus iliopsoas; after muscle relaxation it cants backward as is the case on soft mattresses. The consequent flattening of the lordosis is less pronounced and harmful as compared to a mattress that is too soft. Further, it is clear that people with major spinal disorders (e.g., people with a spinal injury) need special treatment: although a firm mattress induces increased pressure peaks and stress at some places by flexing the spine laterally, it can yield temporary stress relief at the level of injury (Gracovetsky 1987), and might be a preliminary solution (Garfin and Pye 1981). Different types of back pain (such as a herniation and sciatica) are discussed in detail in the final chapter of this book (Chapter 6), as well as the influence of posture—sleeping posture in particular—on back pain.
In order to support the cervical spine correctly, the pillow also should be designed properly (see Figure 1.10). In the case of a lateral position the entire spinal column should form a straight line when projected in a frontal plane. This objective can be realized by both correctly positioning and shaping normal deformable cushions (e.g., kapok cushions) and by correctly designing less deformable structures (e.g., latex cushions).

As opposed to what some manufacturers of sleep systems claim, pressure-relieving mattresses do not necessarily support the spine correctly; at places where body weight is concentrated (i.e., places with a higher weight density), the body will sink deeply into the mattress, causing other zones to rise up.

The heavy pelvic zone will cause the mattress to sag, while the shoulder zone will be pushed upward, resulting in an asymmetrically loaded spine. Correct support of the spine cannot be measured with equipment that generates a pressure distribution output, unless a stringent relation between spinal support and weight distribution is established.

Consequently, in order to evaluate sleep systems with respect to the prevention of low back pain, spinal deformations should be measured. White-light raster line triangulation (WLRT) is one possible measurement technique that is able to describe the shape of the spine in any sleep position between a prone and a lateral position. Therefore, other equipment is needed for a supine position. Chapter 3 thoroughly discusses different techniques to evaluate deformations of the vertebral column during sleep.

Additionally, mattresses with different elastic properties (e.g., a softer shoulder zone or a firmer pelvic zone) are often able to improve the support of the spine, on the condition that the different zones—each with its well-defined elastic behavior—can deform independently. When indenting the hip zone, it should only deform locally without exerting too much influence on either the shoulder zone or leg zone. For example, this kind of “local elasticity” can be obtained by placing pocket springs with different properties in a matrix, allowing them to deform independently. These kinds of mattresses and their influence on posture will be discussed in Chapter 5.

Finally, the dimensions of a sleep system and the ability to adjust the mattress support noticeably improve posture and consequently sleeping comfort. When staying in bed for other activities (e.g., reading), a support structure can add a considerable surplus when it is large enough and when it guarantees correct back support in these alternative positions.

FIGURE 1.10 Optimal support of the cervical spine in a lateral position.
1.1.2 Weight Distribution

During sleep an ischemia (i.e., blood circulation incapacity) will arise in body zones that are in contact with the sleep system. This ischemia generates metabolic substances that stimulate the nerve extremities, which will cause the person to change his or her posture before it gets painful. When sleeping on too firm a surface, body weight will not be distributed homogeneously, and the contact area will be reduced, resulting in increased pressure and shear forces (parallel to mattress surface) on the skin and the underlying soft tissues (e.g., blood vessels). Blood supply will be reduced (or even stopped) due to the deformation of these tissues. Normal capillary arteriolar pressure should vary between 3.3 and 4.6 kPa (25 and 35 mm Hg). Pressure in the venules should approximate 1.6 kPa (12 mm Hg), while critical pressure is considered to be 4 kPa (30 mm Hg). The combined effect of loading time and intensity may result in the development of decubitus ulcers. Hence, most decubitus ulcers occur with people who stay in bed for a long time, especially when the patient cannot be moved because of injuries. Pressure-relieving qualities of a sleep system therefore become fundamental in the case of hospital applications to prevent these ulcers. Also, people who show symptoms of fibromyalgia (e.g., tender points in bony areas) or lipoatrophia (Haex et al. 1998) require an enhanced comfort by optimizing contact pressure.

Many authors (Adams and Hutton 1983, Allen et al. 1993, Rondorf-Klym and Langemo 1993) analyzed the relationship between body postures, the kind of sleep system, body characteristics, and decubitus ulcers. Several of them (Clark and Andrews 1991, Hofman et al. 1994) describe mattress evaluations based on pressure measurements that are easy to perform by means of a mapping system (Nicol and Rusteberg 1993). This consists of a blanket containing a matrix of (capacitive) pressure sensors. The output of each sensor measuring the local pressure is linked to a PC for further processing. Pressure values are calculated in mm Hg or mbar units and can be visualized in different ways, as can be seen in Figure 1.11. In two dimensions, pressures are assigned to different grayscale groups, where darker areas represent areas of high pressures. In three dimensions, pressures are represented in an additional Z-direction. Although often stated otherwise, this type of equipment does not measure whether the spine is supported correctly. Only parts of the data provided by the system can be used to evaluate spinal alignment, on the precondition that these data are supplementary to other measurements or to appropriate user expertise (see Chapter 6).
The general conclusion is that the duration and the level of contact pressure have to be limited to improve the blood and oxygen supply to prevent skin damage and decubitus ulcers. Next to the decreased supplies of nutrients, reduced removal of waste is a component to consider. An increasing number of authors (Bennett et al. 1979, Goossens et al. 1994, Goossens and Snijders 1995) also mention the importance of shear forces to be minimized to prevent stretching and angulations causing thromboses of the blood vessels. Most vulnerable to both phenomena are places where the skin is pinched in between bed and bone, especially because these areas have no fat tissue or muscles to distribute the contact forces. The scapula, the elbow, the sacrum, and the heel therefore are risk areas for a supine position; for a lateral position the ankle, the knee, the larger trochanter region and the shoulder (acromion) are zones to pay attention to. Women generally have a lower risk of developing decubitus ulcers.

1.1.3 Mobility and Stability Promotion

Frequent posture changes during sleep require sufficient mobility; when a mattress is too soft and nearly surrounds the human body, turning around requires a lot of energy or even becomes impossible. Also, mattress hysteresis (see Section 2.1.1.2) should be minimized to avoid exaggerated energy consumption while moving. On the other hand, a stable body support is required to sleep relaxed; when a mattress is too firm, the body is insufficiently surrounded and may roll down in an uncontrolled way. The relevance of these factors increases with age, as it is more difficult for older people to move during sleep. In conclusion, a bed guarantees sufficient rest (1) when changing posture is easy and (2) when each adopted posture is stable.

1.1.3.1 Mobility

Posture changes are necessary to avoid a pressure overloading of soft tissues (see Section 1.1.2) and to prevent muscle stiffness. A regular position shift—about 20 times a night (De Koninck et al. 1992, Dzvonik et al. 1986)—should be sufficient. On some kinds of waterbeds, pressure distributors, or too soft mattresses, the pelvic girdle sinks too deep into the mattress. Because a permanent muscle force application is impossible during sleep, the person will roll back into the cavity when trying to change his or her posture. The consequent extensive periods of immobility are harmful to the muscular system and, possibly, to the respiratory system as well (Chapell 1993).

Although necessary, posture changes have to be limited: switching back and forth too frequently (e.g., when sleeping on a mattress that is too firm) will increase physical restlessness and the tendency to sweat (see Section 1.1.5) during sleep. Further, a consequent unsatisfactory muscle relaxation will impede intervertebral disk rehydration, thus causing back pain indirectly.

In addition, position shifts have to be limited because they influence the consecutive sleeping stadiums. Sleep cycles are strongly related to episodes of immobility, which occur mainly during non-REM sleep (see Section 1.2.8). Immobility usually starts in stadium 2 and ends in stadium 3 or 4 of the same sleep cycle. Suddenly induced position shifts may cause these stadiums, which can be characterized as “deep” sleep, to end prematurely, causing the person to be unfit in the morning.
1.1.3.2 Stability

A stable body position is not guaranteed at all when a sleep system reacts to body movements by oscillating. In that case, the sleeping person will need to apply continuous muscle force in order to stabilize his or her sleeping posture adequately, resulting in some muscle groups being under permanent stress.

In the event of acute back pain, the affected area is protected against sudden body movements, which could provoke pain, by increased tension of the back muscles. Mattress oscillations might interrupt this stable, back-supporting posture, and should be prevented.

1.1.4 Contact Area Optimization

In fact, the optimization of the contact area implies several primary objectives that have been discussed, and therefore it cannot be considered as a goal in itself. On one hand, the contact area should not be too small; when sleeping on too firm a surface, body weight will not be distributed homogeneously, which results in increased pressure and shear forces, giving rise to the symptoms mentioned earlier. It will also be difficult to adopt a stable posture (see Section 1.1.3).

On the other hand, too large a contact area, which is often pursued in order to prevent blood circulation disorders, causes the person to sink deeply into the mattress and limits body mobility (see Section 1.1.3). Further, a large contact area will restrain the skin from breathing and thus increases the tendency to sweat and the uncomfortable feeling of sleeping on a clammy surface.

1.1.5 Microclimate Regulation

The main climate parameters are temperature and humidity, both inside and outside the bed, and in a continuous interaction with the person(s) staying in the bedroom. Detailed recommendations on microclimate regulation are given in Section 6.1.1.

1.1.5.1 Humidity

Fluid absorption and fluid transport to the environment (i.e., ventilation) are the main humidity-related mattress characteristics. The human body emits 200 to 300 mL (up to 1 L) of body moisture each night. One third is emitted through breathing. The remaining two thirds are transmitted through the body surface and have to be absorbed by the mattress (25%) and the sheets, blankets, and pillow (together 75%). This moisture excretion is not to be confused with perspiration, through which much more body fluid is lost (e.g., at the time of a fever or after surgery (Silver et al. 1991)).

Moisture has to be transported to the environment further to avoid a clammy feeling on the mattress surface, to avert mildew formation on the mattress bottom, and to prevent decubitus ulcers, since a moist skin is rough and more sensitive to shear forces. The relative humidity, measured on the location between the skin and the blanket or bed, should stabilize after 20 minutes and should not exceed 65%.

Humidity regulation depends mainly on the top layer of the mattress (80%). The core of the mattress is relatively unimportant (20%), as far as it is able to act as a buffer to
transport the captured moisture between the top layer and the environment. Although some mattress manufacturers might claim the opposite, both synthetic and natural latex cores have an impenetrable skin, which gives them poor ventilation properties compared to spring mattresses. Body movements during sleep do not significantly improve the ventilation capability of a mattress.

In the case of dry weather, room ventilation can be improved by opening a window. Further, warm humid air has to be prevented from floating into colder rooms (e.g., bedrooms) where it might condense, thus obstructing mattress ventilation and creating a seedbed for house dust mites (see Section 1.2.1). Of course, mattress maintenance is an important issue for the preservation of its ventilation properties. Mattresses should be easy to manipulate in order to prevent back problems when turning them around.

### 1.1.5.2 Temperature

The main part of temperature regulation takes place by evaporating water through breathing; the remaining warmth produced by the human body is given out through the skin. Body temperature should stay constant during sleep: when heat insulation is too low, the body will cool off, resulting in muscle stiffness and sleeping disorders. When heat insulation is too high, transpiration will increase, resulting in too high a relative humidity (see Section 1.1.5.1) and consequent sleeping disturbances. An optimal insulating sleep system ensures a bed temperature between 28° and 32°C, allowing the contact temperature to stabilize between 30° and 35°C. Some people report that they wake up automatically when the contact temperature gets too low (e.g., in case of “sheet stealing”).

The insulating capabilities of a bed depend mainly on the core of the mattress and on its top layer(s). A core consisting of natural latex or polyurethane gives higher insulation than springs (e.g., pocket springs). Further, most people prefer warm contact, which largely depends on the capability of the top layer (e.g., wool [Dickson 1984]) to hold air.

Extremely low (−9°C) and extremely high room temperatures (+25°C) must be avoided because they affect the duration of REM sleep. It sometimes is hypothesized that thermal regulation of the body is suppressed during this phase, resulting in the body temperature varying with the environment. A consequent body temperature variation can act as a stimulus to wake up. Further, the optimal room temperature depends on the sleep system, the kind of bed textile, and the person (e.g., age). Generally, low temperatures are better supported by most people, but the lower temperatures are, the higher the risk for mildew formation and the better ventilation should be.

### 1.1.6 Assessment of Physical Factors

Next to the objective measurement techniques cited below, subjective methods also are common to quantify comfort (e.g., in a comparison study on mattresses). These methods can be used for different purposes and are discussed more in detail in relation to psychological factors (see Section 1.3).
1.1.6.1 Spinal Alignment

Spinal alignment can be assessed in many different ways. The majority of Chapter 3 is dedicated to this issue, in view of the importance of this type of measurement. The first section of Chapter 3 discusses and compares all assessment techniques that are appropriate for this kind of measurement. The second section describes the experimental setups that are actually designed and built to measure the spine during bedrest in order to evaluate back support qualities. WLRT (white-light raster line triangulation) is the technique practiced most throughout this book. It is able to scan the back’s surface by projecting raster lines on the surface and by capturing these lines under a known and fixed angle (see Figure 1.12a). Based on surface properties, the line through the processi spinosi, anatomical landmarks (sacrum point, vertebra prominens), and the shape of the spine (see Figure 1.12b) can be calculated accurately.

1.1.6.2 Body Weight Distribution

Body weight distribution is relatively easy to assess by means of pressure interface measurements, which can be performed using a mapping system (Nicol and Rusteberg 1993) that consists of a blanket containing a matrix of (capacitive) pressure sensors. This type of system is placed between the mattress surface and the human body. The output of each sensor measuring the local pressure is linked to a PC for further processing. There are several commercial systems available, such as the Body Pressure Measurement System by Tekscan®, where pressure distribution output on a mattress is mostly represented by a two-dimensional (color or grayscale) diagram (see Figure 1.13), where each square represents one sensor.
 Movements during sleep can be observed with the same measurement systems that are used to assess spinal alignment (see Chapter 3). When only rotational movements or posture changes are relevant, measurements can be carried out in a simpler way, such as by body-mounted sensors like accelerometers, gyroscopes (Mayagoitia et al. 2002), goniometers, and earth-magnetic field sensors (Kemp et al. 1998). Most of these sensors have become small, cheap, robust, and accurate in the last couple of years (Keijsers et al. 2003).

Contact Area Optimization

A pressure mapping system (see Section 1.1.6.2) is able to measure the magnitude of the contact area, but this type of system would be a rather expensive solution for this purpose. A simpler solution might be to position a low-pressure threshold system between the mattress surface and the human body. A sensitive foil (e.g., a foil that changes its appearance (e.g., color) under a certain mechanical load threshold) could be an option.

Humidity and Temperature

Humidity regulation of a sleep system can be measured with adequate equipment, a cross section of which is pictured in Figure 1.14. A cylindrical moisture chamber (39° Celsius, 100% relative humidity) with a cavity on the lower side is placed on the mattress. Moisture transportation through the mattress to the environment (23° Celsius, 50% relative humidity) can be determined by measuring the weight of the mattress.

Heat flow throughout a mattress can be measured in a simple way, as is shown in Figure 1.15.
1.2 Physiological Factors

Physiological reactions of the human body are often a response to the physical condition of the body in its environment. As a result, many of the aspects described below are closely related to the physical factors that are described above. The following section describes the most important physiological reactions of the human body during sleep; guidelines concerning these factors will be described in Chapter 6.

1.2.1 Allergic Reactions

House dust mites are minuscule spiders (0.1 to 0.5 mm) that populate mattresses, carpets, curtains, and pillows in large quantities. A house dust mite allergy is not originated by dust or by the mites themselves. The real cause lies in the allergen “Der PI” which is produced in the intestinal canal of the mites when degrading organic dirt—especially human skin peels—biologically. The mites’ desiccated excrements carrying allergen can be assimilated in the breathing air of man and may thus penetrate into the cavity of the mouth and the lungs, causing allergic reactions (asthma, coughing spells, irritated eyes) that manifest themselves during the night (Owen et al. 1990).
The mites prefer a temperature between 20° and 25°C and relative air humidity between 70 and 75%. A complete extinction of the mites is virtually impossible, but allergic symptoms can decrease by keeping the air humidity lower than 55% or by limiting exposure to the excrements by correct and thorough sanitation: allergen-proof polyurethane coating around the mattress core (Mosbech et al. 1991) and a synthetic top layer that can be pulled off and can be washed above 60°F. Mattresses, therefore, should be easy to maintain.

In addition to a house dust mite allergy, there are many allergies (e.g., latex allergy) that might arise due to chemical substances that are present in the sleep system or environment. These, however, will not be discussed here.

1.2.2 Smoking, Eating, and Drinking

Nicotine is a stimulant, which means it can produce an alerting effect. Smoking before bed makes it, therefore, more difficult to fall asleep. When smokers go to sleep, they experience withdrawal symptoms from nicotine, which also cause sleeping problems. Nicotine can cause difficulty falling asleep, problems waking in the morning, and may also influence REM-sleep (see Section 1.2.8.2.5). Furthermore, literature suggests that smoking propagates accelerated degeneration of the spine (Ernst 1992).

Caffeine is also a stimulant. Caffeine products, such as coffee, tea, colas, and chocolate, remain in the body, on average, from 3 to 5 hours, but they can affect some people up to 12 hours later. The results of several studies confirm the widely held belief that coffee consumption interferes with sleep quantity and quality. In addition, some articles suggest the consumption of caffeine influences the light-dark cycle of our body (see Section 1.2.8).

Alcohol is often considered as a sleep aid because of its sedating effect (Stone 1980), but the overall effect of alcohol on sleep is rather disrupting, because it causes nighttime awakenings (e.g., due to the fact that nighttime alcohol ingestion influences nocturnal breathing in patients with sleep apnea syndrome (see Section 1.2.3) or respiratory diseases). Also, the nocturnal heart rate significantly increases in people who are under the influence of alcohol.

Eating or drinking too much may make you less comfortable when settling down for bed. It is best to avoid a heavy meal too close to bedtime. Also, spicy foods may cause heartburn, which leads to difficulty falling asleep and discomfort during the night.

1.2.3 Respiratory Control

Snoring is a breathing noise that occurs during sleep. It is a common problem among all ages and both genders, but persons most at risk are males and people who are overweight, and symptoms aggravate with age. Snoring is also associated with cardiovascular problems such as high blood pressure, headaches, and diabetes (National Sleep Foundation 2002).

While breathing in, the air passage between the upper soft palate, or uvula, and the throat or base of the tongue may open and close. During sleep, the muscles surrounding these structures relax, and the air passage may narrow or close, causing a blockage of the airway. Air cannot flow through easily and may need to be drawn between these
structures. These tissues then vibrate, which results in snoring. The loudness and tone of the noise are affected by how much air is going through the passage. The greater the obstruction, the greater the effort to draw air, and the louder the noise. As it becomes harder to breathe and snoring gets worse, breathing may actually stop, which is a sign of apnea. Breathing problems occur more often in a supine sleep position rather than lateral sleep position (Cartwright et al. 1991).

Sleep apnea is a serious condition that is far more common than generally understood (Cartwright 2001). It owes its name to a Greek word, apnea, meaning “want of breath” There are two types of sleep apnea: central and obstructive. Central sleep apnea, which is less common, occurs when the brain fails to send the appropriate signals to the breathing muscles to initiate respirations. Obstructive sleep apnea is far more common and occurs when air cannot flow into or out of the person’s nose or mouth, although efforts to breathe continue.

In a given night, the number of involuntary breathing pauses may be as high as 20 to 60 per hour. These breathing pauses are almost always accompanied by snoring between apnea episodes. The frequent interruptions of deep, restorative sleep often lead to excessive daytime sleepiness and may be associated with an early morning headache. Early recognition and treatment of sleep apnea is important because it may be associated with irregular heartbeat, high blood pressure, heart attack, and stroke. Ingestion of alcohol and sleeping pills increases the frequency and duration of breathing pauses in people with sleep apnea.

Pharmacological corrections might be an avenue for treatment of sleep-related airway disorders such as central sleep apnea (Haxhiu et al. 2003). Physical or mechanical therapy, or even surgery, is used as treatment for obstructive sleep apnea. These treatments will be described in Chapter 6.

1.2.4 Cardiovascular Aspects

Cardiovascular problems are often closely related to other sleep-disturbing factors such as the intake of nicotine and alcohol (see Section 1.2.2), the occurrence of sleep apnea (see Section 1.2.3), and shift work. Blood pressure and heart rate variability show significantly increasing trends according to shift work duration (see Section 1.2.8), which suggests that there are negative health effects on the cardiovascular system arising from shift work. Cardiovascular problems are often also related to thermoregulation (see Section 1.2.7). As a result, the treatment of cardiovascular problems is closely related to the treatment of their origin (see Chapter 6 for detailed guidelines).

1.2.5 Hormones—Drugs

Melatonin is a natural hormone that regulates the human biological clock (see Section 1.2.8). It is a natural hormone made by the body’s pineal gland, which lies at the base of the brain. Normally, the body makes melatonin for several hours per night, and melatonin levels are related to the light-dark cycle; as melatonin production rises, alertness and body temperature decrease. Melatonin levels drop again at the end of the night. The body produces less melatonin with advanced age, which may explain why elderly people often have difficulty sleeping and why melatonin supplements improve sleep in the elderly.
The production and sale of synthetic melatonin (to promote sleep), however, are not regulated, and both effects and side effects (such as safety, interactions with drugs, and long-term effects) are not clear, so it should be taken only when supervised by a doctor.

Furthermore, impairment of sleep quality is a common complaint during pregnancy. The literature (Brunner et al. 1994) documents major alterations of the sleep electroencephalogram (EEC, see Section 1.2.9) that are not evident from the sleep polysomnography (see Section 1.2.9) and that may be associated with the characteristic hormonal changes occurring during pregnancy. Some articles (Santiago et al. 2001) suggest the possible predisposition of pregnant women to sleep-disordered breathing. Next to this, menopause is also a source of potential sleeping problems. The hot flashes and associated breathing changes that most women experience during this time appear to disturb sleep and may lead to daytime fatigue. Seventy-five percent of menopausal women suffer from hot flashes, on average for 5 years.

In addition to the influence of hormones, quality of sleep is often affected by the use of drugs. For pain, both doctors and patients frequently consider narcotic drugs, such as codeine. Hypnotics (i.e., drugs that promote sleep) may be prescribed to help those with sleeping difficulties. Even though many drugs are easy to get and often effective, it is not clear how some (combinations of) drugs can interact with pain and sleep. Individuals suffering from sleeping problems should discuss carefully with their physicians the medications they are taking.

### 1.2.6 Headaches

The intimate relationship between sleep and headache has been recognized for centuries, yet the relationship remains clinically complex (Dodick et al. 2003). Headaches associated with nocturnal sleep often have been perceived as either the cause or result of disrupted sleep. Of those who experience the onset of headaches during sleep, 55% report having sleeping disorders. In particular, there is a connection between sleep and tension or migraine headaches. For example, migraine headaches can occur following sleep deprivation or too much sleep. Chronic morning headaches are a good indicator of major depressive and insomnia disorders.

Medical conditions (e.g., obstructive sleep apnea, depression) that may disrupt sleep and lead to nocturnal or morning headache often can be identified on clinical evaluation or by polysomnography (see Section 1.2.9), but recent articles suggest that these headaches are not specific to sleep-related breathing disorders (Jensen et al. 2004), such as the obstructive sleep apnea syndrome. More research will be necessary to reveal the sleep-headache relationship.

### 1.2.7 Thermoregulation

The most known body rhythm is body temperature, which is often used to illustrate a 24-hour biological rhythm (see Section 1.2.8). On average, a healthy person’s body temperature starts to decrease at about eleven o’clock in the evening, and it reaches its lowest point at about four o’clock in the morning. The temperature then rises during the morning, and after a slight mid-afternoon dip (probably related to siesta, see Section 1.2.8), it will rise to its highest value during the early evening. The individual “circadian
phase” depends on the person. The extremes—labeled as morning and as evening types—are well known (Kleitman 1939) and have a different body temperature rhythm (see Figure 1.16).

The natural light-dark cycle (see Section 1.2.8) and normal work schedules tend to suit the lifestyle of morning type subjects but not evening types. Morning types go to bed and rise earlier, but they are unable to compensate late bedtimes by accordingly delayed awakenings. On the other hand, evening types can adjust clock settings easily (because their circadian cycles

![Figure 1.16](image1.png)

**FIGURE 1.16** Evening and morning type temperature (figures vary according to source).

![Figure 1.17](image2.png)

**FIGURE 1.17** Evening and morning type alertness.
are longer than 24 hours and need resetting daily), but cannot adapt their preferred sleep-wake schedule to the imposed schedules. As a result of delayed sleep onset, evening-type subjects often build up a sleep debt during the work week and try to reduce it by extending weekend sleep duration or by napping (Taillard et al. 2003). Under these conditions, it is obvious that subjective and objective sleepiness is higher in evening-type subjects than in morning-type subjects (Kerkhof 1996), especially in the morning (see Figure 1.17).

Heat stress is the product of the interaction of activity and environment (temperature, humidity, etc.) with physiological factors (fitness, hydration, acclimatization, rest, nutrition, medication, health). In ordinary temperatures, sweating will occur, and the body can regulate its internal thermostat. When the environment becomes as warm as the skin, or clothing impedes the evaporation of sweat, the body can no longer regulate itself, and heat stress will occur. Continuous sweating causes excessive loss of body water and salt, which upsets the heat-regulating mechanisms of the body. Hyperthermia is defined as an abnormally high body temperature, which is sometimes induced (as in treating some forms of cancer). Next to the apparent influence of a high ambient (or room) temperature, factors such as sleep deprivation also play an important role in the thermoregulation of the human body (Tobler et al. 1994). Hypothermia is an intense drop in internal (core) body temperature, which can cause brain damage, neurological brain problems, and cardiac arrest. There are several factors associated with hypothermia, such as too low an ambient temperature and inappropriate clothing. When body temperature drops, it can be regained more rapidly by conduction (e.g., contact with a warmer body) rather than by radiation (e.g., room temperature).

### 1.2.8 Sleep-Wake Cycle and Sleep Cycle

#### 1.2.8.1 Sleep-Wake Cycle

The circadian rhythm is the biological cycle that usually occurs at 24-hour intervals and is also known as the biological clock. Our sleep-wake cycle is regulated by this clock and by the body’s need to balance both sleep time and wake time (Van Gelder 2004). The distinct rise and fall of body temperature, plasma levels of certain hormones, and other biological conditions measure these rhythms.

#### 1.2.8.1.1 Personal Differences

Circadian rhythms widely differ among people. Some people only need 5 hours of sleep while others need 10. Also, sleepiness is something personal: people who perform physical labor are usually able to do this with fewer hours of sleep, while people who need concentration or memory tend to feel the repercussion of lack of sleep much earlier. Only a small portion of the population (0.5%) gets by on 4 hours of sleep; these people often do “power naps” to catch up on their sleep. Furthermore, some people work best in the evening (38%), while others prefer the morning (41%); one implication is that the majority of people are not fully alert in the middle of the day—the traditional time for a siesta in hot countries (see Section 1.2.8.1.5). The average sleep time in the Western world is now 6.5 hours.
Recent literature (Grandner and Kripke 2004) suggests that people who sleep for 8 hours or more every night have a higher death rate than those who average 6 to 7 hours, but this study has been criticized because of the subjective measures used. Other studies show that sleeping longer is better, so the actual literature is not consistent on this subject. One could conclude that those who sleep longer, as well as those who sleep for shorter periods, report sleeping problems, but it is difficult to quantify these phenomena.

1.2.8.1.2 Sleep Deprivation

Many scientists are currently studying the effect of sleep deprivation. Experts differ as to whether “shift work sleeping disorder” is a real medical condition, but it is clearly caused by lifestyle. Police, hospital staff, pilots, and people who work at all-night stores are among the workers likely to be affected. However, tolerance to shift and night work is a complex phenomenon related to several aspects pertaining to different domains, dealing with personal characteristics and coping strategies, family and social conditions, working situations, and particularly, work hours organization (Costa 2003).

Drugs are increasingly used to help people with a particular sleeping disorder to stay awake, while the use of drugs is extended from those with sleeping disorders to healthy people who are simply deprived of sleep. This might give people a false sense that they can cheat their need for sleep, while in reality they may be accumulating a sleep debt that will ultimately harm them. Sleep deprivation leads to cognitive impairment, as well as seriously disrupting the immune and hormone systems, although it is not known how long these effects last.

When sleep deprivation occurs, a safe solution would be to not accumulate sleep debt during a longer time, but to catch it up in time in the best possible conditions (e.g., using blindfolds to block out unwanted light while sleeping during daytime).

1.2.8.1.3 Jet Lag

When traveling to a new time zone, our circadian rhythms are slow to adjust and remain on their original biological schedule for several days, which is known as jet lag. Some simple behavioral adjustments before, during, and after arrival can help minimize some of the side effects of jet lag, such as anticipating the time change for trips by getting up and going to bed earlier several days prior to an eastward trip and later for a westward trip. Furthermore, daylight is a powerful stimulant for regulating the biological clock (Yoon et al. 2002), so use blindfolds to block out unwanted light while sleeping, and try to stay outdoors while awake.

1.2.8.1.4 Alzheimer’s

Alzheimer’s is mentioned here because sleep-wake rhythm disturbances observed in Alzheimer’s disease are significantly correlated with the severity of cognitive impairment and often result in institutionalization (Onen and Onen 2003). Alzheimer’s patients show a greater breakdown of the circadian sleep-wake cycle compared to similarly aged nondementia controls. Dementia patients spend their nights in a state of frequent restlessness and their days in a state of frequent sleepiness. The sleep-wake disturbances
in elderly people and particularly Alzheimer’s patients may result from changes at different levels: a reduction of environmental synchronizers or their perception, a lack of mental and physical activity, and age- or disease-related anatomical changes with loss of functionality of the biological clock(s).

1.2.8.1.5 Power Naps—Siesta

Recent literature suggests that taking a “power nap” during the work day may help people to perform better. It is well known that a good night’s sleep consolidates what was learned during the day, but also the effect of a short nap seems to be positive. A short nap largely consists of light sleep (REM sleep, see Section 1.2.8.2),

In many cultures, even in mainland China, there is a noontime rest, or siesta. Generally businesses and schools are closed from noon to 2:00 P.M. After eating lunch, people take a siesta before going back to work or school. During a siesta, deep sleep stages (see Section 1.2.8.2) are also present. Although taking a siesta is common in many cultures, some articles suggest there might be a relation between siesta and mortality in men, but these results are largely attenuated upon exclusion of patients with chronic conditions (Burazeri et al. 2003) and older people. Without persuasive data, recommendations related to this traditional practice should not be made.

1.2.8.2 Sleep Cycle

In the past, sleep was believed to be a passive state. However, sleep as it unfolds is anything but a passive process. The brain’s activity is as complex as during wakefulness, never “resting” during sleep. Furthermore, sleep is essential for normal brain development in early life (Frank et al. 2001).

Measurements of sleep depth without awakening the sleeper were demonstrated first in 1875 by Caton in animals and later (in the 1920s) in humans by Berger (Mathis 1995); both were using the electroencephalogram (see Section 1.2.9). This was soon followed by discovery of the rapid eye movement sleep periods (REM), demonstration of periodical sleep cycles, and their association with REM sleep.

Ever since, human sleep has been described as a succession of five recurring stages: four non-REM stages and the REM stage. A sixth stage, waking, is often included. Waking, in this context, is actually the phase during which a person prepares for sleep. Rapid eye movement (REM) sleep is marked by extensive physiological changes, such as accelerated respiration, increased brain activity, eye movement, and muscle relaxation.

Sleep quality changes with every transition from one sleep stage into another. Although the signals for transition between the stages of sleep are unclear, these stages are discretely independent of one another, each marked by subtle changes in bodily function and each part of a predictable cycle whose intervals are observable. Sleep stages are monitored and examined clinically with polysomnography (see Section 1.2.9), which provides data regarding electrical and muscular states during sleep.
1.2.8.2.1 Awake

The waking stage is referred to as “relaxed wakefulness,” because this is the stage in which the body prepares for sleep. When a person is awake and active, brain activity (EEG, see Section 1.2.9) is characterized by beta waves. When a person is awake and relaxed, brain activity is characterized by alpha waves (see Table 1.1). All people fall asleep with tense muscles, their eyes moving erratically. Then, normally, as a person becomes sleepier, the body begins to slow down. Muscles begin to relax, and eye movement slows to a roll.

1.2.8.2.2 Stage 1

Stage 1 sleep, or “drowsiness,” is often described as first in the sequence, especially in models where waking is not included. Polysomnography shows a 50% reduction in activity between wakefulness and stage 1 sleep. The eyes are closed during stage 1 sleep, but if aroused from it, a person may feel as if he or she has not slept. People awakened from stage 1 sleep often remember

**TABLE 1.1 Brain Waves during Sleep**

<table>
<thead>
<tr>
<th>Sleep Stage</th>
<th>Freq. (Hz)</th>
<th>Ampl. (mV)</th>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Awake</td>
<td>&gt;12</td>
<td>10–30</td>
<td>Beta (mostly)</td>
<td>Low amplitude, high frequency</td>
</tr>
<tr>
<td></td>
<td>8–12</td>
<td>20–50</td>
<td>Alpha (relaxing)</td>
<td>Higher amplitude, lower frequency</td>
</tr>
<tr>
<td>Stage 1</td>
<td>8–12</td>
<td>20–50</td>
<td>Alpha (brief periods)</td>
<td>(when compared to beta)</td>
</tr>
<tr>
<td></td>
<td>4–8</td>
<td>50–100</td>
<td>Theta (mostly)</td>
<td>Higher amplitude, lower frequency</td>
</tr>
<tr>
<td>Stage 2</td>
<td>2–7</td>
<td>50–100</td>
<td>Theta</td>
<td>(when compared to alpha)</td>
</tr>
<tr>
<td></td>
<td>12–14</td>
<td>20–100</td>
<td>Spindles</td>
<td>Sudden increases in wave frequency</td>
</tr>
<tr>
<td></td>
<td>2–7</td>
<td>&gt;100</td>
<td>K-complexes</td>
<td>Sudden increases in wave amplitude</td>
</tr>
<tr>
<td>Stage 3</td>
<td>2–4</td>
<td>50–100</td>
<td>Theta (mostly)</td>
<td>See above</td>
</tr>
<tr>
<td></td>
<td>0.5–2</td>
<td>100–200</td>
<td>Delta (&lt;50%)</td>
<td>Higher amplitude, lower frequency</td>
</tr>
<tr>
<td>Stage 4</td>
<td>0.5–2</td>
<td>100–200</td>
<td>Delta (mostly)</td>
<td>(when compared to theta)</td>
</tr>
<tr>
<td></td>
<td>2–4</td>
<td>50–100</td>
<td>Theta (&lt;50%)</td>
<td>See above</td>
</tr>
<tr>
<td>REM</td>
<td>&gt;12</td>
<td>10–30</td>
<td>Beta</td>
<td>See above</td>
</tr>
<tr>
<td></td>
<td>8–12</td>
<td>20–50</td>
<td>Alpha</td>
<td>See above</td>
</tr>
</tbody>
</table>

*Note: Figures may vary according to source.*
fragmented visual images. Many also experience sudden muscle contrac-tions (hypnic myoclonia), which are often preceded by a sensation of starting to fall. Stage 1 may last for 5 to 10 minutes and is characterized by theta waves (see Table 1.1).

### 1.2.8.2.3 Stage 2

Stage 2 is a period of light sleep during which polysomnographic readings show intermittent peaks and valleys, or positive and negative waves. These waves indicate spontaneous periods of muscle tonus mixed with periods of muscle relaxation. Muscle tonus of this kind can be seen in other stages of sleep as a reaction to auditory stimuli. The heart rate slows, and body temperature decreases. At this point, the body prepares to enter deep sleep. Stage 2 is characterized by theta waves that are interrupted by spindles and K-complexes (see Table 1.1).

### 1.2.8.2.3 Stage 3

Stages 3 and 4 are deep sleep stages—with stage 4 being more intense than stage 3—and it is very difficult to wake someone during these stages. They are known as slow-wave sleep, or delta sleep (see 1.2.9). During slow-wave sleep, the electromyogram records slow waves of high amplitude, indicating a pattern of deep sleep and rhythmic continuity. In stage 3 these waves begin to appear and are interspersed with smaller, faster waves.

### 1.2.8.2.4 Stage 4

By stage 4, the brain produces delta waves almost exclusively. There is no eye movement or muscle activity. People awakened during deep sleep do not adjust immediately and often feel disoriented for several minutes after they wake up. Some children experience bed wetting, night terrors, or sleepwalking during deep sleep.

### 1.2.8.2.5 REM

REM sleep is distinguishable from non-REM sleep by changes in physiological states, including its characteristic rapid eye movements. Our eyes move down to midline, just as in wakefulness, and begin to move sporadically.

However, polysomnograms show wave patterns in REM to be similar to stage 1 sleep. In normal sleep (in people without disorders of sleep-wake patterns or REM behavior disorder), heart rate and respiration speed up and become erratic, while the face, fingers, and legs may twitch. Intense dreaming occurs during REM sleep as a result of heightened cerebral activity, but paralysis occurs simultaneously in the major voluntary muscle groups, including the sub-mental muscles (muscles of the chin and neck). Because REM is a mixture of encephalic (brain) states of excitement and muscular immobility, it is sometimes called paradoxical sleep. It is generally thought that REM-associated muscle paralysis is meant to keep the body from acting out the dreams that occur during this intensely cerebral stage. The first period of REM typically lasts 10 minutes, with each recurring REM stage lengthening, and the final one lasting an hour.
1.2.8.2.6 Waves

Table 1.1 summarizes the five sleep stages mentioned above and their characterizing brain waves.

1.2.8.2.7 Cycles

The period of non-REM sleep (referred to as “NREM”) is comprised of stages 1–4 and lasts from 90 to 140 minutes, each stage lasting anywhere from 5 to 20 minutes. Surprisingly, however, stages 2 and 3 repeat backward before REM sleep is attained. So, a normal sleep cycle has this pattern: waking, stage 1, 2, 3, 4, 3, 2, REM (see Figure 1.18).

The five stages of sleep, including their repetition, occur cyclically. The first cycle, which ends after the completion of the first REM stage, usually lasts for 100 minutes. Each subsequent cycle lasts longer, as its respective REM stage extends. A person may complete five cycles in a typical night’s sleep.

1.2.8.2.8 Age

The percentage of REM sleep is highest during infancy and early childhood, drops off during adolescence and young adulthood, and decreases further in older age. By the time babies are 1 year old they can recognize a lot of sounds and even simple words, and it is suggested (Cheour et al. 2002) that they might progress this fast because they learn language while they sleep.

![FIGURE 1.18 Sleep stages.](image)

as well as when they are awake. However, it is not known how babies accomplish this nighttime learning.

The stage-respective dimensions of sleep change relative to age. Stages 3 and 4 in the first sleep cycle shorten even more dramatically in older people than they do during a typical night for everyone else, so older people get less total deep sleep than younger
people do. Also with age comes the lengthening of the first REM stage. Older people commonly enter REM sleep quicker and stay there longer.

1.2.8.2.9 Disturbing Factors

Sleep deprivation, frequently changing sleep schedule, stress, and environment affect the progression of the sleep cycle. Rapid eye movement latency may be affected by a sleeping disorder like narcolepsy. Psychological conditions like depression shorten the duration of rapid eye movement. Also, treatment for psychiatric conditions often positively affects sleep, typically inducing some desired change in sleeping habit. For example, antidepressants usually quicken sleep onset and lengthen REM stages. People who take antidepressants often benefit from the effects they have on the quality and duration of the sleep cycle.

1.2.8.2.10 Waking Up

For thousands of years people did not wake up until dawn, while at present most people are woken up by an alarm clock. Spontaneous awakening is optimal; it occurs when a normal sleep-wake cycle is followed and when the hours of falling asleep and waking up are not significantly altered. In this case, sleep stages have adjusted their rhythm in such a way that—even when an alarm clock is used—awakening occurs more or less naturally during light sleep, as illustrated in Figure 1.19.

![Spontaneous vs. forced awakening](image)

**FIGURE 1.19** Spontaneous vs. forced awakening.
People who are awakened during deep sleep (e.g., because the hours of falling asleep and waking up are significantly altered or because sleep time is too short) do not adjust immediately and often feel disoriented for several minutes after they wake up (see Figure 1.19). Waking up also feels very unpleasant. In this case, an alarm clock that gradually increases its intensity may be able to wake up a person in a forced, but gradual way (see start to end in Figure 1.20). The same result can be obtained by an alarm clock that gives two or more pulses (see 1 and 2 in Figure 1.20) with an interval of 10 to 15 minutes and with an increased intensity. The aim of both methods is to make the actual awakening happen during light sleep. Figure 1.20 represents an optimal achievement of this objective, which is surely not always the case.

1.2.9 Assessment of Physiological Factors

Many parameters relating to the physiological factors cited above are relatively easy to measure, while they are not specific to sleep measurements. These parameters—such as body temperature, blood pressure, and heart rate—will not be discussed here. Other parameters are relatively difficult to measure (e.g., nicotine intake, respiration), but are not exclusively related to sleeping either. Also, these will not be considered in detail here. A separate or combined measurement of these parameters can be made (e.g., cardiac vibrations, respiration and posture can be measured simultaneously by piezoelectric sensors, attached to the chest) (Miyamoto et al. 2002).

For parameters specifically related to sleep, it is important to perform measurements (e.g., sleep depth) without awakening the sleeper, which can be done by using the electroencephalogram (EEC). Multiple studies and steady discoveries have made polysomnography, with its ability to perform simultaneous whole-night recordings of EEC, electromyogram (EMG), and electrooculogram (EOG), a major diagnostic tool in study of sleeping disorders.

First, gross brain wave activity is considered, as measured by an EEG. This machine provides the electrical activity of the brain. Second, muscle tonus is measured with an EMG machine. Third, eye movement is recorded via an EOG. The EEG reading is the most important measure in differentiating between the stages, while the EMG and EOG...
are most important in differentiating rapid eye movement (REM) sleep from the other stages. Figure 1.21 shows a polysomnography for different sleep stages.

Polysomnographic measurements have been of critical importance in evaluating the interaction between sleep and physiological changes such as cardiovascular control (Murali et al. 2003). In addition to EEG, EOG, and EMG, eye movement, muscle activity, heart rate, respiratory effort, air flow, and blood oxygen levels can be measured. Thanks to polysomnographic measurements the effects of sleep can be objectively differentiated from the effects of rest and recumbency. Also, the specific effects of sleep onset and termination and the effects of different sleep stages can be assessed.

When measuring sleep, subjective measures or self-evaluations are often used and are valuable. They show, however, a higher level of vulnerability to external and motivational factors (Curcio et al. 2001).

1.3 Psychological Factors

Despite the importance of psychological factors (e.g., the influence of a depression on sleep), a detailed description is not within the scope of this study, so only a very brief description will be given here.

1.3.1 Environment

The bedroom should be attractive, inviting for sleep, and free of interruptions. Sleeping aids may vary widely, depending on personal preferences. Some factors are clearly related to physiological factors, but they can be a source of annoyance or irritation as well, so care should be taken to design the sleep environment to establish the conditions that are needed for sleep—cool, quiet, dark, comfortable—and to check the room for
distractions, including a bed partner’s sleep disruptions such as snoring, light, and a dry or hot environment.

### 1.3.2 Relaxation

A bedtime ritual is a powerful “cue” that it is time to sleep. A relaxing, routine activity before bedtime conducted away from bright lights sends a signal to the body that it is time to go to sleep and will make it easier to fall asleep. Activities before going to bed include reading, taking a bath, and listening to the radio and depend on personal preferences. Also, meditation is increasingly used in the West. Activities such as problem-solving before bedtime should be avoided.

Those finding it hard to sleep often seek distraction, and some distractions work better than others. Thought suppression (where the idea is to suppress an anxious or negative thought as soon as it pops up) is a much-tried option, but counting sheep—another much-praised possibility—does not always work according to the literature (Harvey and Payne 2002), as opposed to conjuring up a pleasant and relaxing scene. Furthermore, people seem to disengage more from images compared with verbal thoughts (Nelson and Harvey 2003).

### 1.3.3 Assessment of Psychological Factors

For the assessment of psychological factors many different subjective measures (such as self-evaluations or questionnaires) and behavioral measurement techniques are used. For example, Lahm (Lahm and Iaizzo 2002) used qualitative scales. One possibility is to use a scale to rank different conditions according to personal preferences. Another possibility is to rate different conditions on a scale of 1 to 10 (1 being the least preferable and 10 being the most preferable). Still another option is to use the psychophysical technique of magnitude estimation, which involves having subjects rate a set of test conditions relative to a standard condition (to which an arbitrary comfort rating (e.g., 100) is assigned. For example, if subjects judge a condition to be twice as good as the standard, they would give it a rating of 200. This scaling method has the advantage of yielding a true ratio scale, rather than an ordinal (rank) scale, which gives better statistical analysis options.

### 1.4 Cultural and Historical Aspects

#### 1.4.1 Cultural Diversity

##### 1.4.1.1 Anthropometrical Differences

**1.4.1.1.1 Body Dimensions**

The length of a sleep system should be at least body length plus 0.20 m (see Chapter 2), while the mechanical properties of a sleep system should be optimized according to anthropometrical properties, such as body weight and body contours (see Chapter 5). As
a result, differences in anthropometrical characteristics (Pheasant 1996) will automatically result in different sleep systems.

### 1.4.1.1.2 Sleeping Posture

The most important difference between Asian people and other population groups (such as Caucasian, African, or Indian) is that Asians tend to sleep more in a supine sleep position, while others prefer a lateral sleep position. (This proposition should not be interpreted too strictly, as 25% of Caucasian people also sleep in a supine position, and vice versa.)

As further explained in Chapter 2, most Caucasians probably sleep in a lateral position because knees and hips can be bent in this position, and legs can be lifted (see Figure 2.31). This results in a slight smoothening of the lumbar spine, which is needed to approximate the natural (unloaded) shape of the vertebral column. However, a supine sleep position seems to have advantages as well: people who sleep in this position have a larger contact area than side sleepers, which translates to less weight per square meter of the body. Furthermore, body contours that are in contact with the bed are less pronounced (e.g., as opposed to wide shoulders in a lateral position), which reduces the necessity for local material variations (e.g., a softer shoulder zone, see Chapter 5), which simplifies the design of an adequate sleep system. In conclusion, a supine sleep posture makes fewer demands on sleep systems, but not many Caucasians seem to prefer it.

In a lateral sleep position, optimal support gives rise to the spinal column being a straight line when projected in a frontal plane (see Figure 1.7) in order to achieve a symmetrical loading of the spine. In a supine sleep position, the spine should maintain its natural curve (the same thoracic kyphosis and lumbar lordosis as in the upright position, yet slightly smoothened, see Section 1.1.1.2). As a result, when looking at publications intended for commercial purposes, European and American advertising clearly focuses on a lateral sleep position while Asian publicity concentrates on a supine position, and the corresponding support of the cervical and lumbar area (see Figure 1.22).
The logical question is why Caucasians prefer a lateral sleep position, which potentially makes more demands on the sleep system, and Asians do not. Although it is tempting to attribute the posture difference to cultural sleeping habits only, there seems to be evidence that anthropometrical properties also play a role.

First, there are indications that there are differences in lumbar curvature in different races (Saulicz 2000). Some authors (Mosner et al. 1989), however, attribute these variations to apparent differences (measured externally, including muscular structures) than to actual differences (measured from radiographs). If the lumbar curvature in Asians is indeed flatter in comparison to other population groups, this would imply that Asians would experience less discomfort from sleeping on a hard surface (see Figure 1.23). In Caucasian people, the gap in between the lumbar curve and the bed surface will cause the pelvis to cant backward (see Figure 2.34), which results in increased muscle tension because the legs stay in a horizontal position.

Second, there seems to be evidence (Goonetilleke et al. 1996) that spinal shape changes related to posture are different in the Asian and other population groups. Goonetilleke investigated the variations in spinal shape in seven postures corresponding to different trunk-thigh angles (70, 80, 90, 100, 110, 120, and 180°) for a total of 20 subjects (10 Hong Kong Chinese and 10 Indians). Results indicate two different patterns for the two populations, where the influence of trunk-thigh angle on the lumbar spine is very small for the Chinese population. For Caucasians, the relation between backward pelvic rotation and lumbar flattening was confirmed earlier for seating postures by radiographic studies (Andersson 1987). These results would imply that most Asian people sleep in a supine position because they do not benefit from a lateral sleep position as Caucasians do. Bringing the thighs slightly closer to the trunk (as is the case in a semi-Fowlers’ position, with bent knees [135°] and hip joints [45°]) has no significant influence on their lumbar spine. Further study is however needed on this subject.

The question then rises where these interpopulation differences come from. A possible answer might lie in the hip joint, and especially the constitution of the head of the femur (the upper leg bone) in different population groups. When we look at the neck-shaft angle, which is determined as the angle between the shaft axis and the femoral neck axis in a frontal projection (β in Figure 1.24), and at the ante-version angle, which is determined as the angle between the shaft axis and the femoral neck axis in a transversal plane (α in Figure 1.24), we see large interpopulation differences.
The ante-version angle $\alpha$, which measures 10 to 15° in a grown individual, is found to be higher in Asians when compared to Caucasians (Mahaisavariya 2002). Furthermore, there is evidence that the neck-shaft angle $\beta$, which measures about 135°, is larger in Caucasians when compared to Asians. It is clear that such a different skeletal constitution of the femoral neck involves a different muscular arrangement and a different ligament structure around the hip joint. It is plausible that these differences are responsible for the dissimilar relation between trunk-thigh angle and lumbar spine flattening for different population groups. However, in order to quantify these differences, this subject has to be studied further in detail (e.g., by three-dimensional simulations).

**FIGURE 1.24** Femoral dimensions.

The final question is how the theory of evolution can explain these different musculoskeletal body constitutions. Did man adjust his posture to the environmental needs, which eventually led to changes in his musculoskeletal structure, or did he adapt his behavior to his musculoskeletal structure? Anderson and Trinkaus (1998) give an answer on (a part of) this question, by collecting data on femoral neck shaft angles for 30 modern, historic, and prehistoric human population samples. When analyzing data with respect to sexual dimorphism, bilateral asymmetry, geographical patterning, and general economic level, there appears to be a significant increase in mean neck-shaft angles across populations with an increasingly sedentary existence and with mechanization. The last reflects the developmental plasticity of this feature with respect to habitual load levels during ontogeny of the hip region.

In short, the hypothesis (see Figure 1.25) is that different habitual load levels (as a result of urbanization or sedentary life) led to differences in musculoskeletal body constitution between population groups. These musculoskeletal differences involved different musculoskeletal kinematics and dynamics, such as the proportional relation (or otherwise) between backward pelvic rotation and lumbar flattening. Finally, these altered spinal shape changes (related to posture) involve different sleeping postures: Caucasians generally sleep in a lateral position, in order to flatten the lumbar spine, and Eastern people usually sleep in a supine position, where the pelvis does not cant backward. As a result Eastern people are able to sleep perfectly well on a futon, while most Caucasians are not.
FIGURE 1.25 Why do Caucasians and Asians sleep differently?

On one hand, the hypothesis above is plausible and might be even related to interpopulation seating differences. On the other hand, it is clear that each link of the hypothesis chain above has to be studied further to give a decisive and quantitative answer.

1.4.1.2 Local Sleeping Habits

Adult sleepers in traditional societies recline on skins, mats, hammocks, wooden platforms, the ground, or just about anything except a thick, springy mattress. Pillows or head supports are rare, and people sleep in whatever they happen to be wearing. Virtually no one in these traditional societies, including children, keeps a regular bedtime. Individuals tend to slip in and out of sleep several times during the night. In these unplugged worlds, darkness greatly limits activity and determines the time allotted to sleep. People frequently complain of getting too much sleep, not too little.

Next to the variation of bed type, there are large differences in sleeping habits, especially “co-sleeping.” Solitary infant sleeping is a principally Western practice, quite young in terms of human history (50 to 200 years old). Today in many cultures the practice of co-sleeping continues, with babies and children seen as natural extensions of their mothers for the first years of life, spending both waking and sleeping hours by her side. Examples of cultures that practice some form of co-sleeping include the Japanese, Koreans, Phillipinos, Eskimo Indians, the Kung San of Africa, and natives of Okinowa.

Furthermore, it must be noted that many of the descriptions below are anecdotal rather than actually representing the genuine sleep culture of a country. Only a limited number of countries are discussed.

1.4.1.2.1 Asia

Despite the fact that most Asian countries are influenced a lot by industrialization and by Western culture, it is remarkable that traditional sleep cultures still persist to a large extent. One possible explanation might be the differences in body constitution and
sleeping posture (see Section 1.4.1.1), making “soft” Western sleep systems not always suited for the Asian population. Furthermore studies have demonstrated that sleep duration is shorter in (especially East) Asia, compared with Europe, North America, South America, and Africa.

1.4.1.2.1 China—Traditionally, people in China do not use a mattress like people do in the Western world. Instead, there is a board covered with a thin padding, covered with one colorful sheet. The top bedding is folded up during the day with the pillow on top. In the heat of the summer, a straw or bamboo mat is placed on the floor instead of a raised platform, because the coolest air is at the floor level. Many Chinese living in larger cities (such as in Hong Kong or Shanghai) have Western style beds and bedding.

Western-like adjustments include laying straw, a cotton quilt, a palm fiber rug, or a sponge mattress on the board to make it softer. Spring beds did not come into Chinese life until the 3rd plenary session of the 11th Central Committee.

Furthermore, there is a noontime nap in Mainland China. Generally, businesses and schools are closed from noon to 2:00 P.M. After eating lunch, people take a nap before going back to work or school.

1.4.1.2.1.2 Japan—“Futon” is a Japanese word that translates as “bedding” and originally referred to the pillow (“makura”), the traditional sleeping mat made of cotton (the “shike” or bottom futon, see Chapter 2), and the thick cotton quilt called the “kake” (top) futon. The various coverings and sheets used with these are originally included in the name futon as well, but they fall beyond the scope of this description. The word futon as it has been imported into current Western usage, variously refers to a futon mattress, a slat bed base, and the combination of both of these. Also commonly (and incorrectly) referred to as futon are small couches that consist of a slat base and a cotton mat that can be converted to a bed.

A shike futon is usually stuffed with cotton batting and wrapped in “shikifu” (sheets). The Japanese use different types of futon depending on the season, such as light ones in summer and heavy ones in winter. Cotton is able to absorb large quantities of moisture—Japan is very humid, especially in the rainy season—but it starts feeling clammy at low moisture levels. Drying the futon is extremely important. It can be done by airing it daily or by using a futon dryer (Kansouki), which is placed between the bottom futon and the top futon while they are spread on the floor. A futon is usually put away during the day in a closet called an “oshiire.” Japanese houses are usually small and do not have many rooms, so rooms are used for dual purposes: during the day, a bedroom can be used as workroom or guestroom once the futon is stored.

Traditionally, a futon is placed on a tatami (see Chapter 2), consisting of the heri (the cloth of the tatami), the omote (made of tightly woven rush grass), and the doko (made of compressed rice straw). In more Western versions an insulation board made of other materials (such as compressed wood chips or foam) replaces the rice straw.

1.4.1.2.1.3 Korea—Traditional Korean bedding is known as “ondol.” A rigid base or floor is heated by a system of flues built under the flooring, with a translucent yet durable paper on top of it (known as “changhoji”). Early ondol systems were fueled by hot smoke from a wood fire. Today the heat source is more likely to be oil or electric. This floor is considered to be the bed, on top of which a thin mattress is placed, called a “yo.”
In many places, such as apartments, people may stow away mattresses or sleeping materials out of the living quarters during the daytime. Children’s mattresses may be stored in the parents’ room.

1.4.1.2.1.4 Southeast Asia (Laos, Vietnam, Cambodia, Thailand, Indonesia)—Most people in Southeast Asia sleep on a hard wooden platform that is raised above the ground (usually about 0.5 m). This platform is made of hard wood, slatted, or bamboo and covered by a reed mat. Doors often are left open to let cooler air in, there are no curtains on the windows, and nets are put around the bed to keep the mosquitoes away.

Furthermore, family members often share a platform—wealthy parents also share a bed with children—but the exact type of sharing depends on local habits. Sometimes (e.g., in North Vietnam), mother and daughters share a bed and the father shares a bed or room with their sons. In Cambodia, families often live in one or two rooms, and everyone sleeps on the same wooden platform, sometimes covered by a straw mat. Sleeping places in the home are determined according to status: parents sleep at the “head” end and the youngest children sleep at the “foot.” In traditional Indonesian culture (Nas 1998), grown boys, men, and strangers without a wife lodge and sleep together in the community building of the village (Sumatra). The mother sleeps together with the children and unmarried girls (Mentawai), or unmarried sons and daughters sleep together (Timor).

1.4.1.2.1.5 India—In India, sleep habits and beds may vary widely depending on the region and the population class. Also in India, communal sleep is quite common: children may sleep in a room with the entire immediate family, while families of relatives sleep in other rooms of the shared house.

Furthermore, in India many towns and villages are characterized by masses of people living on the main street, selling their wares, eating, drinking, bathing, and sleeping. At night, wooden framed beds with rope woven mattresses line the roadsides.

1.4.1.2.1.6 New Guinea—The traditional Gebusi are rainforest dwellers who grow fruit in small gardens and occasionally hunt wild pigs and practice a kind of communal sleep. Women, girls, and babies crowd into a narrow section of a community longhouse to sleep on mats. Men and boys retreat to an adjacent, more spacious longhouse area, where they sleep on wooden platforms.

1.4.1.2.2 Africa

In many African cultures, bed sharing is quite common; in northern Kenya’s Gabra tribe, fathers sleep with their sons and daughters with their mothers. Furthermore, it is known that Ngando infants sleep with their mothers at night, while Aka infants sleep with (a part of) the family.

Sleeping habits and beds vary widely depending on the region. For example, the Kung in northwest Botswana sleep on the ground, and the Efe pygmies in Zaire (who appear to be the ultimate forest people) sleep on thinly strewn leaves. However, not many researches have conducted comparative anthropologic studies on sleeping for this continent, which is regrettable.
### 1.4.1.2.3 Latin America

People in most countries in Latin America have sleep habits that are similar to those of the Western world. However, the native Indian population used to have different sleep habits that were passed on to some extent.

The most typical type of bedding characterizing the tropical areas is the hammock. Almost every country in Central America, including Guatemala, Nicaragua, El Salvador, Costa Rica, and Mexico, as well as countries in South America such as Brazil, Venezuela (e.g., the South Venezuelan Hiwi), and Ecuador, have been using and enjoying hammocks for close to 1000 years. Hammocks were widely spread by sailors, who both traded and used them. If it gets colder, a sheet may be used for cover.

A hammock is a suspended bed, usually of netting, canvas, or leather. The bark of the hamack tree was the first material used to make them. As time progressed, the sisal plant was used in place of bark. People discovered the material to be more durable, abundant, and when the material was beaten with a rock, the fibers were softened, making the hammock even more comfortable. The use of cotton in hammocks has only been around for 60 years. While the plaited hammock seems to be native to the Western Hemisphere, blankets have served the same purpose among primitive tribes in other parts of the world.

When going more south or north, out of the forested areas, overnight protection from animals such as scorpions, mites, and serpents gets less important, which is why people in these regions (such as the Paraguayan Aches) do not sleep on hammocks but on mats. Another common practice in these regions (e.g., Honduras) is to sleep on a straw mattress with tattered quilts covering most of the soiled linens.

### 1.4.1.2.4 North America

Sleep systems here are quite comparable to those used in Europe, which are described in Chapter 2. Only the dimensions are different (North-American sleep systems tend to be thicker), and some types of beds are used more frequently (e.g., box springs) while others are used less often (e.g., latex mattresses). However, the native Indian population used to have different sleep habits, which can be compared to the actual Asian population (e.g., sleeping on wooden platforms, see Section 1.4.1.2.1) rather than to the Indians currently living in the forested areas of South America.

### 1.4.1.2.5 Europe

European sleep systems are discussed in Chapter 2. Apart from local variations—people in northern Europe prefer latex mattresses (because of the better heat insulation) while people in southern European countries prefer spring mattresses—and apart from local habits—some Russians change bed sheets daily—differences are relatively small.

### 1.4.1.2.6 Arab World

Sleep systems here are quite comparable to those used in Europe, except from peoples that traditionally live in tents, such as the Bedouin. Bedu, the Arabic word from which the name bedouin is derived, means “inhabitant of the desert” and refers generally to the desert-dwelling nomads of Arabia, the Negev, and the Sinai. Traditionally nomads, in the
winter Bedouins may have separate stone houses for women and for men. During the
summer, they sleep on mattresses in open-sided tents made from goat-hair. Such a tent is
customarily divided into two sections by a woven curtain. One section, reserved for the
men and for the reception of most guests, is called the “mag’ad” or sitting place. The
other, in which the women cook and receive female guests, is called the “maharama,” or
“place of the women.”

1.4.2 Evolution of Sleeping Behavior

Few characteristics of sleep in the past have been examined. Apart from references to the
sleep habits of communities before the industrial revolution (Ekirch 2001), only the
subject of dreams has drawn sustained attention (Steiner 1996). However, as it is widely
accepted that most changes in sleep behavior have taken place during this revolution, this
section concentrates on those changes.

1.4.2.1 Sleep in the Pre-Industrial Era

Sleep granted men and women of all ranks some measure of relief from daily cares as
well as an interval of hard-won rest from their labors. Sleep’s principal contribution was
not merely physiological but psychological. Thus, according to London street slang,
falling asleep was to “forget oneself.” Retiring to bed for most laborers, if only on a thin
mattress of straw, must have been welcome indeed, all the more since few claimed
furniture of any greater comfort.

1.4.2.2 Sleep Duration

It is not entirely clear at what time people went asleep and for how long they were
sleeping before the industrial revolution. Diaries, though heavily weighted toward the
upper classes, suggest that adults typically slept for periods of from 6 to 8 hours and that
the standard time for retiring to bed fell between nine and ten o’clock. In truth, however,
few adults beneath the upper ranks probably enjoyed the opportunity to sleep more than 7
or 8 hours.

1.4.2.3 Wealth

Before the industrial revolution the household’s beds were typically the most expensive
articles of family furniture. Between the fifteenth and seventeenth centuries, beds evolved
from straw pallets on bare floors to wooden frames complete with pillows, sheets,
blankets, coverlets, and “flock mattresses” which were typically filled with rags and stray
pieces of wool. Affluent homes boasted elevated bedsteads, feather mattresses, and heavy
curtains. Rich families invested heavily in superior beds not only as a mark of social
prestige but also for their greater comfort.

The sleep of the working poor remained vulnerable to the vexations of everyday
existence, as their quarters lay more exposed to unwelcome intrusions, including frigid
temperatures, annoying noises, and voracious insects. Inadequate bedding meant that
families in the lower ranks routinely slept two, three, or more to a mattress, with
overnight visitors included. Sharing not only the same room but also the same covers conserved resources and generated welcome warmth. Probably most parents slept apart from children other than infants, although occasionally entire households of European peasants shared the same beds (Jervis 1772). Some families also brought farm animals within the sleeping quarters at night. Besides protecting cows, sheep, and other livestock from predators and thieves, boarding with beasts also allowed greater warmth.

1.4.2.4 Sleep Deprivation

Ordinary men and women most likely suffered some degree of sleep deprivation, feeling more fatigued upon awakening at dawn than when retiring at bedtime. If complaints are to be believed, the work of laborers was erratic and their behavior lethargic. Chronic fatigue probably afflicted much of the population before the industrial revolution. Napping during the day appears to have been common, with sleep less confined to nocturnal hours than it is in Western societies today.

1.4.2.5 Segmented Sleep

Until the close of the early modern era, Western Europeans on most evenings experienced two major intervals of sleep bridged by up to an hour or more of quiet wakefulness. The initial interval of slumber was usually referred to as “first sleep” or, less often, “first nap” or “dead sleep.” In French, the term was premier sommeil; in Italian, primo sonno and in Latin, primo somno or concubia nocte. The intervening period of consciousness bore no name, other than the generic term “watch” to indicate a period of wakefulness that stemmed from disinclination or incapacity for sleep. The succeeding interval of sleep was called “second” or “morning” sleep. Both phases lasted roughly the same length of time, with individuals waking sometime after midnight before ultimately falling back to sleep.

It is tempting to explain this pattern of broken sleep as a cultural relic rooted in early Christian experience, e.g., because monks were required to rise after midnight for the recital of verses and psalms. Conversely, in the twentieth century, some non-Western cultures with religious beliefs other than Christianity have long exhibited a pattern of sleep remarkably similar to that of preindustrial Europeans. As an example, anthropologists have found villages in Africa to be surprisingly alive after midnight with newly roused adults and children. Furthermore, there is reason to believe that segmented sleep, such as many wild animals still exhibit, was the natural sleep pattern before the modern age.

The reason for segmented sleep lies in darkness: in attempting to recreate conditions of “prehistoric” sleep, researchers (Wehr 1996) found that human subjects, deprived at night of artificial light over a span of several weeks, eventually exhibited a pattern of broken sleep. Without artificial light, subjects first lay awake in bed for 2 hours, slept for 4, awakened again for 2 to 3 hours of quiet rest and reflection, then fell back asleep for 4 more hours before finally awakening for good. On the physiological impact of modern lighting—or, in turn, its absence—on sleep, there is wide scientific agreement; changes in levels of the brain hormone melatonin and in body temperature are among the most apparent consequences (see Section 1.2.8).
1.4.2.6 Sleep Interval

Commonly, people used the interval of solitude for a moment of contemplation; at no other time during the day or night were distractions so few. Furthermore, because exhaustion prevented workers from copulating upon first going to bed, intercourse seems to have occurred mostly after the first sleep. For the poor, awakening in the dead of night presented opportunities of a different sort: never during the day was there such a secluded interval in which to commit acts of petty crime.

1.4.2.7 Dreams

As in previous eras, dreams played a profound role in early modern life. However, the impact of dreams in the preindustrial Western world never became as enduring as it has long been in non-Western societies. Not only do dreams in some African cultures still provide a critical source of guidance, they also constitute alternate realms of reality with distinctive social structures. Among the Alorese in the East Indies, entire households are awakened once or several times each night by family members anxious to communicate fresh visions.

1.4.2.8 Lighting

Beginning in the late seventeenth century, divided sleep, with its interval of wakefulness, became less common with the passage of time, first among the propertied classes in better-lit urban neighborhoods, then slowly among other social classes. Not until the early nineteenth century would darkness be eroded by industrialization and the continued growth of leisured affluence among urban middle and upper classes. Professional policing, nocturnal trade, evening employment for workers and, most important, improvements in both domestic lighting and the illumination of public streets increasingly rendered night less obscure. Light from a lone gas mantle proved 12 times as strong as that from a candle or oil lamp, while light from a single electric bulb by the close of the nineteenth century was 100 times more powerful. Today, we inhabit a nonstop culture characterized by widespread electric lighting both inside and outside homes and businesses.

1.5 Conclusion

Sleep is a natural periodic suspension of consciousness during which processes of rest and restoration occur. The cognitive, reparative, and regenerative accompaniments of sleep appear to be essential for maintenance of health. This chapter discussed the most important ergonomic factors affecting the quality of sleep, including physical, physiological, and psychological aspects. When concentrating on normal healthy people and thus on the prevention of eventual disorders, back support qualities are of primary importance, and should be optimized. The optimal sleep system has to support the human spine such that it adopts its natural position, which is assumed to be the same as it takes in the upright position, yet slightly smoothened by the fact that, in a sleep position, the direction of the gravitation vector no longer coincides with the cranio-caudal direction of
the body. All other aspects are secondary and can only be optimized if no harm is done to support qualities, while keeping in mind that peak values (e.g., pressure peaks) should always be avoided. In conclusion, mechanical properties should be optimized within the limitations posed by nonmechanical preconditions.

References


Chapell, M.S., Respiratory problems during sleep in infants and the elderly and possible relation to mattress compression, *Sleep*, 1993, 16(4), 391.


Which ergonomic factors affect the quality of sleep? 45


2

Bed Type Variety—Sleeping Posture Diversity

An overview of the most important ergonomic factors affecting the quality of sleep—including physical, physiological, and psychological ergonomic parameters—was discussed in the first chapter. This chapter focuses on the underlying determinants of the previously discussed physical factors, including (a) the influence of different types of support structures for the human body and (b) the influence of different postures.

When looking at the physical aspects of sleeping, the spine—with its spinal cord—is undoubtedly one of the most vital and vulnerable organs of the human body and will be protected consciously and unconsciously (e.g., by optimizing body posture in order to unload the vertebral column). While seated, as for most awake activities, this will happen in an active way by adapting body posture, such as by adjusting chair properties, or by switching to other activities. During sleep, however, it is the sleep system (i.e., mattress+base+head cushion) we are “lying and relying” on that mainly affects posture.

In fact, a resting place should create perfect conditions—a state resembling weightlessness—and permit us to move freely in order to be able to optimize our body position unconsciously, but in reality most sleep systems force us in a certain position (prone, supine, or lateral), leaving few possibilities left to minimize spinal deformations. Due to this imperfection, the sleep system plays a leading role in protecting the spine, whereas the influence of body posture is limited to an initial and conscious selection (prone, supine, or lateral), and a subsequent unconscious and relatively minor optimization. Consequently the design of sleep systems (and the correct assignment to different population classes; see Chapter 5) is of primary importance at this stage in the optimization of the physical aspects of sleep quality. Efforts to design new concepts of sleep systems that have a less forceful impact on sleeping posture are made in parallel with this optimization process, in order to achieve better sleeping conditions in the long term, but are not described in detail here.

2.1 Different Types of Sleep Systems

As discussed in the Chapter 1, people in the Western world did not think about sleeping on a well-supported structure until recently; people used to sleep on a sagged, worn-down mattress placed on a worn-down spring base. In the late 1950s, a firm bed was promoted for the prevention of low back pain, and many people started to put a wooden board under their mattress, this being a typical solution that insufficiently corrects the support properties and may cause ventilation problems. Currently, the definition of a correct sleep system is much more differentiated, as was discussed in the first chapter. The recent historical evolution of sleep systems is illustrated in Figure 2.1. Today a bed generally consists of a mattress, a mattress support, a frame, a head cushion, and a blanket. This
section discusses how these different parts can be designed and combined in order to obtain an adequate sleep system.

Section 2.1.1 briefly illustrates all the basic material properties (column I in Figure 2.2) that are needed to define the physical characteristics of a sleep system (column II in Figure 2.2). Section 2.1.2 discusses different types of sleep systems (e.g., mattress varieties) and reveals the influence of their physical properties on general physical ergonomic properties (column III in Figure 2.2). The flowchart in Figure 2.2 illustrates how different characteristics on different levels influence each other.

**FIGURE 2.1** Recent historical evolution of sleep systems.

<table>
<thead>
<tr>
<th>I</th>
<th>II</th>
<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material properties</td>
<td>Sleep system properties</td>
<td>Ergonomic properties</td>
</tr>
<tr>
<td>3. …</td>
<td>3. …</td>
<td>3. …</td>
</tr>
</tbody>
</table>

**FIGURE 2.2** Impact flowchart.

Furthermore, different mattress types (both core and top layers) and bed base varieties are discussed in relation to each other, notably which kinds of supports can be combined with each of the different mattress classes. Also head cushions are discussed in brief.

**2.1.1 Basic Material Properties**

At first sight, material properties seem to be a question of personal preference; in reality this is only partly true, which is why one should try to adjust material properties—as many as possible—to personal needs in an objective way. For example, it is clear that heavier persons need a firmer mattress in order to avoid the pelvic girdle from sinking too deeply into the mattress. Materials, therefore, have to be developed and combined in order to optimize general sleep system characteristics.

While the material density mainly affects fatigue resistance, material elasticity—and the combination of materials with a different elasticity—guarantees correct support of the human body. Furthermore, it is possible to obtain the required characteristics with different material types by defining or adjusting these materials in a correct way. Latex
elasticity can be adapted by changing mold specifications (e.g., use of indentations),
designing spring dimensions enables the modification of pocket spring mattresses, and
polyurethane mattress elasticity can be adjusted by the use of different kinds of foam
(e.g., different densities).

Standardized compression and tensile tests are able to describe most mechanical
properties: displacement-controlled benches measure force at a fixed interval, resulting in
a force-displacement characteristic consisting of a loading and a relaxation phase, which
can be recalculated to a stress-strain characteristic.

2.1.1.1 Elasticity

Elasticity can be calculated as the ratio of stress to strain: the more force is needed to
reach a certain indentation, the firmer the mattress will be, as can be seen in Figure 2.3.
In the case of a perfectly elastic material, elasticity will

![Image of force-indentation characteristics](image)

FIGURE 2.3 Force-indentation characteristics of a firm (left) and a soft (right) polyurethane mattress.

![Image of hysteresis](image)

FIGURE 2.4 High hysteresis (left) of a viscoelastic foam and low hysteresis (right) on a latex mattress.

be constant. In the case of a viscoelastic material (e.g., polyurethane), elasticity depends
on the velocity of deformation.
2.1.1.2 Hysteresis

Mattress hysteresis can be determined by calculating the area between the load curve and the relaxation curve (see Figure 2.4). It measures the energy that is dissipated in the mattress and should be minimized to avoid exaggerated energy consumption while moving.

2.1.1.3 Fatigue Resistance

Mattress density measures the weight per unit of volume and is related to the fatigue resistance of a mattress: the higher the density, the higher the resistance to fatigue. Standard polyurethane (PU) foams and latex foams with higher densities generally have a higher stiffness, as illustrated in Figure 2.5, where stiffness is measured at a compression of 40%. This relation makes it difficult to produce PU mattresses with a good resistance to fatigue (high density) while keeping good elastic properties. Recently developed chemical processes allow the production of highly elastic polyurethane foams (with a stiffness level as low as 2.5 kPa) with relatively high densities (up to 60 kg/m³), in other words including latex-like grades, as illustrated in Figure 2.5. The average elasticity of latex mattresses, however, remains larger than the average elasticity of polyurethane mattress (see Figure 2.5).

For standard polyurethane foams—and to a certain extent also for latex—the relation between stiffness and density continues outside Figure 2.5 for other applications (e.g., composite PU foam with a density of 100 kg/m³ and a stiffness of 15 kPa).

Also related to the fatigue resistance of mattresses is the resilience of foam, which refers to its ability to spring back into shape. Highly resilient foams are particularly good at showing this buoyant effect and are designed to ensure, for example, that cushions retain their shape for years to come. Despite the fact that highly resilient foams mostly have a relatively low density (ranging from 28 kg/m³ up to 37 kg/m³), they have a good resistance to fatigue and good elastic properties.
2.1.1.4 Dimension

The dimensions of a sleep system noticeably influence sleeping comfort. Bed width should be at least shoulder width plus 0.40 m; length should be at least body length plus 0.20 m; bed height should be at least 0.45 m (for ventilation purposes) while high beds (+0.55 m) make it easier to get in or out (Mannekens 1996). When staying in bed for other activities (e.g., reading) a support structure can add considerable value when it is large enough, when it guarantees correct back support in these alternate positions, and when it can easily be adjusted from one position to another.

Beds that are constructed for two people such as queen size beds or similar (1.60 m×2.00 m approximately) have an understructure that spans the entire width of the bed. In order to avoid any vertical deflection in the middle, these structures need the aid of a central leg. European beds are often split and have a central leg set up by default to avoid tilting toward the center of the bed—not always successfully however.

As illustrated in Table 2.1, standard dimensions of sleep systems (dimensions given are for double beds) depend on demographical aspects, where anthropometrical parameters such as body length play a prominent role (Centraal Bureau voor de Statistiek 1996, Kroemer and Granjean 1997, Pheasant 1996).

### TABLE 2.1 Dimensional Diversity of Sleep System

<table>
<thead>
<tr>
<th>Country</th>
<th>Sleep System Width (Average, m)</th>
<th>Sleep System Length (Average, m)</th>
<th>Female Body Length (Average, m)</th>
<th>Male Body Length (Average, m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holland</td>
<td>1.60</td>
<td>2.10</td>
<td>1.696</td>
<td>1.825</td>
</tr>
<tr>
<td>Germany</td>
<td>1.60</td>
<td>2.00</td>
<td>1.635</td>
<td>1.745</td>
</tr>
<tr>
<td>U.S.A.</td>
<td>1.50</td>
<td>2.00</td>
<td>1.625</td>
<td>1.755</td>
</tr>
<tr>
<td>U.K.</td>
<td>1.50</td>
<td>2.00</td>
<td>1.610</td>
<td>1.740</td>
</tr>
<tr>
<td>France</td>
<td>1.50</td>
<td>1.90</td>
<td>1.600</td>
<td>1.715</td>
</tr>
<tr>
<td>Japan</td>
<td>1.40</td>
<td>1.90</td>
<td>1.530</td>
<td>1.655</td>
</tr>
</tbody>
</table>

2.1.1.5 Fluid Permeability

During sleep, moisture has to be transported to the environment in order to avoid a clammy feeling at the mattress surface, to avert mildew formation at the mattress bottom, and to prevent decubitus ulcers, since a moist skin is rough and therefore more sensitive to shear forces. One third of this moisture is emitted through breathing; the remaining two thirds are transmitted through the body surface and have to be absorbed by the mattress (25%) and the sheets, blankets, and head cushion (together 75%). As a result, the fluid permeability of a material (e.g., in the mattress or the head cushion) is directly related to (a) the fluid absorption capabilities of a sleep system and (b) the fluid transport from the human body to the environment (i.e., ventilation), which are the two main humidity-related physical characteristics of a sleep system.
2.1.1.6 Heat Insulation

Body temperature should stay constant during sleep. When heat insulation is too low, the body will cool off resulting in muscle stiffness and sleeping disorders; when heat insulation is too high, transpiration will increase, resulting in a too high relative humidity (see Section 1.1.6.5) and, consequently, sleeping disturbances. Thus, heat insulation properties of materials, especially of those materials used for the core of a mattress and for its top layer(s), are of prime importance when optimizing climate regulation.

2.1.1.7 Variation and Combination of Basic Material Properties

When building a mattress with different physical properties at different locations (e.g., a softer shoulder zone or a firmer pelvic zone), it is important that different zones—each with its well-defined elastic behavior—are able to behave independently in case this behavior is needed. When the hip zone is indented, for example, it should only deform locally without exerting too much influence on either the shoulder zone or leg zone. For example, this kind of “local elasticity,” which is sometimes also referred to as “conformity” (Mannekens 1996), can be obtained in different ways, such as by placing (pocket) springs with different properties in a matrix, allowing them to deform independently, as illustrated in Figure 2.6.

![FIGURE 2.6 Conformity.](image)

2.1.2 Sleep System Properties

The following section describes the different parts a bed usually consists of: a mattress, a base, a head cushion, sheets, and blankets. The main task of the mattress, the base, and the head cushion (which together make up the sleep system) is to support the human body correctly, where the mattress itself consists of a core with one or more top layers, surrounded by a cover. The main function of the sheets and blankets is to regulate the climate.

2.1.2.1 Mattress Core

Generally four kinds of mattresses are produced in the Western world: foam mattresses (e.g., polyurethane), latex mattresses (e.g., synthetic latex), spring mattresses (e.g., biconical spring mattress) and fluid-based beds (e.g., waterbeds). Next to these varieties, natural materials (e.g., kapok or straw) are also produced to a lesser degree in other parts of the world.
2.1.2.1 Polyurethane Foam Mattresses

Polyurethane is a synthetic material that obtains its flexibility through foaming; the material can be applied to perform different functions (e.g., insulation, bedding, coating). Foam mattresses consist of a cellular network (Figure 2.7) giving the material a specific density, elasticity, and air permeability. On a microscopic scale, standard polyurethane cells have a nonisotropic open structure. The cell structure can be adjusted from fine to coarse (about 25 to 8 cells per linear cm), and from regular to irregular, or can imitate a natural sponge pore, depending on the application.

The fact that one can achieve a wide variety of (stiffness) characteristics is one of the main advantages of polyurethane. Further, most polyurethane foams are light and, therefore, easy to manipulate. A polyurethane foam mattress core should have a thickness of at least 0.12 m and a density of at least 35 kg/m³ (which partially contradicts manipulation requirements) to obtain reliable fatigue resistance. In principle, polyurethane foams with higher densities have a higher stiffness. New chemical processes, however, allow the production of mattresses with a high density without a stiffness that is too high (see Section 2.1.1.3).

Standard polyurethane mattress cores give reasonable body support thanks to small hysteresis and reasonably good elastic behavior. They give good heat insulation and have reasonable moisture permeability. Polyurethane foams, however, can be adjusted from highly elastic to viscoelastic.

Viscoelastic—sometimes called slow-recovery—polyurethane foams have a high hysteresis and are used whenever this property is demanded (e.g., medical applications, sound insulation, joint seals in buildings). Finally, highly resilient polyurethane foam cells (see Section 2.1.1.3) have a differentiated, isotropic, and open structure; the material density is higher. Minimal hysteresis and perfect elasticity give these mattresses very good support qualities; fatigue resistance and moisture transportation are optimal; heat insulation is very good, as is the case for most polyurethane foams.

On a macroscopic scale, polyurethane mattress core properties are not necessarily homogeneously distributed; these characteristics may vary along the width or the length.

FIGURE 2.7 Cellular network of polyurethane.
of a mattress to create different comfort zones such as a softer shoulder zone in combination with a firmer pelvic zone.

2.1.2.1.2 Latex Foam Mattresses

Latex mattresses consist of a block of foamed rubber particles and sometimes are called rubber foam mattresses. Rubber particles are of synthetic or natural origin—combinations are possible—and can be foamed firmly or softly. Natural latex mattresses generally contain 80% natural latex, completed with synthetic additives, which are necessary in order to process rubber to latex and to obtain the required elastic properties. Latex is formed by molding and vulcanized to be dimensionally stable and resistant to temperature fluctuations. As opposed to highly elastic polyurethane mattresses, latex foams show a rather strict relation between density and firmness (see Figure 2.5).

Latex is especially suited for the fabrication of mattresses with different stiffness zones. Thanks to adequate mold design a material cut-away obtains a softer elastic behavior when requested (Figure 2.8). Another advantage of

![FIGURE 2.8 Latex mattress with different stiffness zones.](image)

the high elasticity of latex is that thinner layers can be used, reducing the potential for wear and the restriction of vapor transport.

Each zone with well-defined elastic properties is able to deform independently of other zones; when indenting the hip zone, it only deforms locally without exerting influence on either the shoulder zone or leg zone. Latex, therefore, presents perfect support qualities when the mattress is conceived well; an air chamber with an adjustable volume can even improve the support in the lumbar area. Further, latex is pliable, heavy, and consequently difficult to manipulate; it has low air permeability, but offers very good heat insulation.

2.1.2.1.3 Spring Mattresses

Spring mattresses exist in all kinds of shapes, dimensions, springs, and spring connections. Only the spring core and the top and bottom comfort layers—both synthetic and natural foams—are common. The design of the springs, notably the wire thickness, is mainly responsible for the elastic properties of these kinds of mattresses. Their main advantage is that spring stiffness can be adjusted generally (in order to suit different
population classes) or locally (to combine different comfort zones such as a softer shoulder zone with a firmer pelvic zone). Sometimes springs and foam are combined over the entire volume to combine spring advantages (good ventilation) with foam benefits (heat insulation and good elastic behavior).

Bi-conical springs—also called “Bonell springs” in the case of mattress applications—are cone-shaped compression springs having a smaller diameter in the middle (D₂ in Figure 2.9) compared to the extremities (D₁ in Figure 2.9). Springs are mounted independently next to each other and are linked by spiral wires on both sides.

In some applications bi-conical springs are designed with a variable pitch to provide a near constant spring rate, as is the case for most classical (cylindrical) types of springs (see Figure 2.10). In the case of mattress applications, however, there is no constant spring rate due to the fact than no variable pitch is used. Consequently, Bonell springs, which are typically used in mattresses, do not have a constant stiffness in the usual range of deformation and offer an enlarged resistance against increased loading, as illustrated on the right of Figure 2.10.

**FIGURE 2.9** Spring mattress (left) and single bi-conical spring (right).

**FIGURE 2.10** Cylindrical spring (left) and bi-conical spring (right).

**FIGURE 2.11** Pocket spring mattress with different stiffness zones (left) and pocket springs with different stiffness (right).
Endless-spring cores consist of one single woven steel wire linking small cylindrical springs together, which guarantees more flexibility. Pocket springs (Figure 2.11) are mostly cylindrical or barrel-shaped (larger diameter in the middle compared to the extremities) and are individually wrapped up into pockets. Pocket springs are mounted into rows—perpendicularly to the cranio-caudal direction—and are able to deform almost independently from each other, so that they can be used to create different stiffness zones in a mattress.

Generally, spring mattresses offer a rather low heat insulation and reasonable body support; pocket springs offer good body support and slightly better heat insulation (15%) compared to normal springs, but still 50% less than standard foam mattresses.

2.1.2.1.4 Cotton Mattresses

Cotton is a strong, natural vegetable fiber obtained from the exterior of the seeds of various species of *Gossypium* native to India, the Sudan, and Ethiopia. It contains 88 to 96% pure alpha cellulose; the remainder is protein, pectin, sugar, oil, and wax (Cook 1984). Early civilizations in Egypt, China, India, and Peru wove cotton fabrics; it became widespread in the Western world in the Middle Ages for different applications, such as mattress filling. At present, it is still used for this purpose in some countries (see Chapter 1).

Cotton fibers have a length of 1.6 to 6 cm and look like flattened twisted tubes in the microscope (see Figure 2.12). The elasticity of the fibers is limited (5–10% elongation), which results in cotton mattresses having poor elastic properties. They have good moisture absorption qualities and could have reasonable fatigue resistance, if moisture is transported and aired well, which is often not the case. Cotton mattresses have poor heat insulation properties.

**FIGURE 2.12** Photomicrograph of cotton (200×enlarged).

2.1.2.1.5 Kapok Mattresses

Kapok consists of short, lightweight cellulose fibers obtained from the seeds of the silk cotton tree, *Eriodendron anfractuosum*, primarily grown in Java, Africa, Brazil, India,
and Central America. Kapok consists of 43% alpha cellulose, 24% pentose, 15% lignin, and 6.6% uronic anhydride (Cook 1984). The soft fibers have a smooth surface and are transparent. Kapok is buoyant and will support up to 30 times its own weight. The fluffy fibers are too brittle to spin and are used for filling mattresses, head cushions, and life jackets. Like cotton, kapok has good moisture absorption but poor heat insulation properties.

2.1.2.1.6 Straw Mattresses

Bedstraw is a natural red dye obtained from the roots of the *Galium* species plants native to England and northern parts of Europe. Some examples are *Galium verum*, commonly known as ladies bedstraw, and *Galium mollugo*, commonly known as hedge bedstraw (Schweppe 1997). The stems of the plants were used for stuffing mattresses in medieval times and are still used in some countries. A traditional tatami is also filled with rice straw (see Section 2.1.2.4.7). Straw mattresses are far from ideal: they have poor elastic properties and are not suited for people susceptible to grass allergy, etc.

2.1.2.1.7 Shike Futon Mattresses

“Futon” is a Japanese word meaning “bedding” and originally refers to both the pillow (“makura”), the traditional sleeping mat made of cotton (the “shike” or bottom futon that is discussed in this paragraph), and to the thick cotton quilt called the “kake” (top) futon, which is discussed later. The various covers and sheets used with these are originally included in the name futon as well, but they fall beyond the scope of this description. Figure 2.13 pictures the traditional futon elements on top of a “tatami” base.

![Futon elements](image)

**FIGURE 2.13** Futon elements.

As it has been imported into current Western usage, the word futon variously refers to a futon mattress, a slat bed base, and the combination of both of these. Also commonly referred to as futon are small couches that consist of a slat base and a cotton mat that can be converted to a bed. Diverging even further from the original concept, a futon is often combined with a box spring bed base or a polyurethane mattress, partly to add comfort artificially due to the lack of soft tatami flooring (see Section 2.1.2.4.7) in the Western world.
A shike futon is usually stuffed with cotton batting and wrapped in “shikifu” (sheets). Japanese use different types of futon depending on the season, lighter ones in summer and heavier ones in winter. Cotton is able to absorb large quantities of moisture—Japan is very humid, especially in the rainy season—but it starts feeling clammy at low moisture levels. Drying the futon is extremely important, by airing it daily or by putting a futon dryer (“kansouki”) between the bottom futon and the top futon while they are spread on the floor. Cotton has poor heat insulation properties, but it is antibacterial and is therefore tolerated well by allergic people.

It is commonly said that sleeping on futons on the floor is better for the back than sleeping on a soft bed, which is advice that probably dates back to the seventies, when sleeping on a firm surface was recommended. However, the spinal column will be supported incorrectly, as explained before (cf. Section 1.1): in case of a lateral position only places with a large body width—the shoulders and the hip zone—will be supported; the lumbar region will bend down, especially in people who have a more pronounced body contour, which is very harmful. When sleeping in a supine position, the pelvis is first canting forward under influence of tension in the musculus iliopsoas; after muscle relaxation it will cant backwards, which is harmful to some extent. Since most Western people sleep in a lateral position (see Chapter 1), sleeping on a futon without an additional comforter (a soft overlay that is placed between the futon and the body) will be painful rather than relieving.

As opposed to this, Eastern people usually sleep in a supine position, where the pelvis is not canting under the influence of tension in the musculus iliopsoas (which is due to a different musculoskeletal body constitution; cf. Section 1.4). As a result, Eastern people are able to sleep perfectly well on a futon.

![Mattress sagging](image)

**FIGURE 2.14** Mattress sagging.

### 2.1.2.3.8 Fluid-Based Beds

When sleeping on too firm a surface, body weight will not be distributed homogeneously, and the contact area will be reduced, which results in increased pressure and shear forces (i.e., parallel to mattress surface) on the skin and the underlying soft tissues, such as blood vessels (Bennett et al. 1979, Goossens and Snijders 1995). Sophisticated beds for hospital applications, such as alternating pressure (Stewart et al. 1990) or fiber-filled mattresses (Mita et al. 1997), generally achieve good contact pressure distribution to improve the blood and oxygen supply, which will prevent skin damage and eventual
decubitus ulcers. Standard waterbeds (free flow, without any support material added) do not, however, necessarily offer better pressure distribution compared to standard foam or latex mattresses, even though this is often stated by manufacturers.

On the other hand, pressure-relieving mattresses in general do not necessarily support the spine correctly; places where weight is concentrated will sink deeply into the mattress, causing other zones to rise (see Figure 2.14). The heavy pelvic zone, consequently, will cause the mattress to sag, while the lifted shoulder zone will be loaded asymmetrically. Furthermore, the large contact surface will limit mobility—due to the body sagging into the mattress—while water oscillations obstruct stability in case only one fluid chamber is employed. However, both pressure-relieving and spine-support qualities have been improved during the last 5 years (e.g., by adding foam elements to standard waterbeds; see Section 2.1.2.1.9). Waterbed mattresses that minimize wave motion are also available, while most types are able to provide warmth in order to speed relaxation.

Finally, impermeable beds generate a microclimate with much higher temperature and relative humidity (60 to 70%) compared to a normal mattress (37%); an adequate top layer that is ventilated regularly may prevent humidity transportation problems.

2.1.2.1.9 Material Combinations

An evolution has taken place recently, where different materials are combined to achieve a better combination of desired mattress properties. More precisely foams, springs, and fluids are combined in order to build mattress cores that offer both good back support and good pressure distribution.

On one hand, classical foam mattresses (e.g., latex, type A in Figure 2.15) that traditionally offer good back support (see Sections 2.1.2.1.1 and 2.1.2.1.2) are equipped with fluid (e.g., air chambers, such as the ADS® (Air-Dämpfungs-System) mattress by Scharaffia®, type B in Figure 2.15) in order to optimize pressure distribution characteristics. On the other hand, classical fluid beds (e.g., water, type D in Figure 2.15) are filled with foam to optimize stiffness characteristics (e.g., by creating several independent fluid chambers or by adding foam layers; see type C in Figure 2.15) to offer better back support. Design features include cushiony foam, air baffles, or rows of springs along the edge of the mattress to provide a buffer for the bed frame. It is plausible

**FIGURE 2.15** Fluid-foam combinations.
that fluids and foams will be combined more frequently and more interwoven in future sleep systems.

Next to these fluid-foam combinations, foams (both latex and polyurethane) are sometimes combined with metal springs. One possibility is to provide holes in a foam block to insert metal springs; another possibility is to combine metal springs with foam springs, as is done in TwinSpring® mattresses (see Figure 2.16). These springs consist of two parts that fit perfectly into each other: the inner part is made of metal; the outer part is made of high-density polyurethane foam. The properties of both springs can be varied along the length and width of the mattress in order to provide better (personalized) body support, and the entire system of springs is then sandwiched between two layers of latex to provide better pressure distribution. The advantage of this kind of system is that relatively good properties are achieved (air permeability, durability, back

![FIGURE 2.16 Spring-foam combination.](image)

**TABLE 2.2 Mattress Core Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Properties</th>
<th>Fatigue Resistance</th>
<th>Fluid Absorption/Permeability</th>
<th>Heat Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyurethane foam</td>
<td>− to ++</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Latex foam</td>
<td>+ to ++</td>
<td>+</td>
<td>−</td>
<td>++</td>
</tr>
<tr>
<td>Springs</td>
<td>− to ++</td>
<td>+</td>
<td>++</td>
<td>− to +</td>
</tr>
<tr>
<td>Cotton and kapok</td>
<td>−</td>
<td>−</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Straw</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Futon</td>
<td>− to +</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Fluid</td>
<td>− to +</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Material combinations</td>
<td>+ to ++</td>
<td>+</td>
<td>− to +</td>
<td>+</td>
</tr>
</tbody>
</table>

*Note: “−”=bad; “+”=good; “++”=very good.*
support, pressure distribution) without using large volumes of relatively expensive materials (e.g., latex).

2.1.2.1.10 Summary

Mattress core properties for the various kinds of mattresses are summarized in Table 2.2.

2.1.2.2 Mattress Top Layers and Covers

Humidity regulation of a sleep system depends mainly on the top layer of the mattress; the core of the mattress plays a less important role. Top layers have insulating and protecting purposes and are usually treated against bacteria and mildew formation. Depending on the kind of mattress, the cover may be stretchable or not and detachable or not; some are stretchable to avoid shear forces. Covers generally can be subdivided into covers that are stitched to the tick (with a limited stretch) and core covers. To properly contour the body and not sag, the cover of the mattress must be able to become larger (e.g., by stretching) to expand its surface area. To a certain degree, lack of stretch materials will increase the need for a zoned mattress as a compensation for the lack of mobility at the surface.

The use of a top layer—synthetic or natural—that can be taken off and can be washed above 60°C is the best prevention of allergy to the house dust mite (Mosbech et al. 1991, Owen et al. 1990). Wool, silk, cotton, and linen are common natural top-layer materials; acrylic, polyester, rayon, and nylon are synthetic top-layer materials. In the following, the elasticity, allergic activity, heat insulation, and moisture absorption of these materials are discussed. These properties relate to the avoidance of shear stress, the prevention of house dust mite allergy, and the regulation of climate which, respectively, are the three most important characteristics of the mattress top layer.

FIGURE 2.17 Photograph of wool.

It is clear that the properties of the materials described below can be largely altered by using different weaving techniques or by adding chemical substances.

2.1.2.2.1 Wool

Wool is obtained from the fleece of sheep and is composed of keratin. The term wool is also used for a small amount of hair that is obtained from camels, alpacas, Angora rabbits, Angora goats, Kashmir goats, llamas, and vicunas. Wool fibers have a hollow
core, or medulla, surrounded by a shaft called the cortex (Cook 1984). The cortex is covered with a layer of cells called epithelial scales—under the microscope they look like scaly corkscrews. The size and shape of the scales are characteristic of the source of the fiber. Wool fibers can range in color from white to brown to black and have a length from 38 to 375 mm (see Figure 2.17). They are stretchable and long lasting, do not wrinkle, and spring back into shape, which allows the fibers to better recuperate during the daytime.

Wool is able to absorb wet vapor up to 33% of its own weight without feeling clammy; moisture is first diffused and then slowly evaporated to the environment. Thanks to this absorption quality, wool fiber avoids sudden cooling off in case of great temperature changes. Further, it is able to hold a lot of air for heat insulation purposes (Dickson 1984) and has good flexibility (elongation up to 50%) in order to avoid shear stresses at the contact surface.

Minor points are the facts that wool picks up static electricity easily when rubbed, and that it is susceptible to moth larvae and other protein-feeding insects.

2.1.2.2.2 Silk

Silk is a fine, lustrous natural fiber obtained primarily from the cocoon of the caterpillar of the mulberry silk moth, *Bombyx mori*. Silk is indigenous to China, which was able to maintain a monopoly on the production of silk fabric for almost 3000 years. Silk fibers contain a fibroin protein that can be decomposed with acid to form a mixture of amino acids (Cook 1984): glycine (41.2%), alanine (33.0%), serine (16.0%), and tyrosine (11.4%). Raw silk appears as two strands that are held together with a kind of gum, which is removed by boiling the fibers in soapy water. Silk is often treated with salts to increase its density; weighted silks, however, degrade more rapidly (Brooks et al. 1996).

Silk is elastic (elongation up to 30%) and able to absorb moisture up to 40% of its own weight, quickly evaporating it to the environment, making it especially suited for people who emit lots of moisture. It is not able to hold air within its structure for heat insulation purposes, but has an anti-allergic activity (it is resistant to moths, bacteria, and fungi, but susceptible to carpet beetles).

2.1.2.2.3 Cotton

Cotton—which was discussed earlier in relation to mattress filling—is able to absorb large quantities of moisture, but it starts feeling clammy at low moisture levels (typically 8% of the weight of the cotton). It has poor elastic properties (elongation of only 5 to 10%) and poor heat insulation properties, which makes it only suited for summer. Furthermore, it is susceptible to mildew, bacteria, and silverfish, but is resistant to moths and beetles and is tolerated well by allergic people. For example, a futon may be wrapped in spun cotton.

2.1.2.2.4 Linen

Linen is a fabric woven from flax fibers, especially from the *Linum usitatis-simum* plant native to the Mediterranean region and the Atlantic coast of Europe (Cook 1984). To
obtain the fibers, the flax plants are harvested, dried, retted, crushed, then washed and cleaned. They are thinner and longer than cotton, but the fiber tube has thicker walls, resulting in a stronger thread. Microscopically, linen fibers have knots and joints that are not seen on cotton. Flax is used to make linen clothing (see Figure 2.18), bookbinding thread, fish line, twine, and paper.

Linen has similar heat insulation and moisture absorption capacities as cotton and is therefore considered a cool fabric for a warmer climate. It is, however, much stronger, not elastic (elongation of 2% only), and resistant to mildew, insects, and pests (Collings and Miller 1978). Silverfish (a silver-gray wingless insect) will eat starched flax.

**FIGURE 2.18** SEM micrograph of linen fabric.

mildew, insects, and pests (Collings and Miller 1978). Silverfish (a silver-gray wingless insect) will eat starched flax.

### 2.1.2.2.5 Acrylic

Acrylic is a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polymer composed of at least 85% of acrylonitrile units. DuPont first commercially manufactured acrylic fibers in 1950. Under the microscope the fiber is dog-bone shaped with apparent cut ends (Cook 1984). The smooth, thermoplastic fibers are resistant to wrinkles, chemicals, UV light, insects, mildew, and moisture. They produce fabrics that are nonallergenic, lightweight, soft, durable, and fast drying. They are, however, susceptible to heat and will melt or burn (Joseph 1986). Acrylic fibers are used for carpets, blankets, drapes, outdoor products, and apparel such as sweaters, coats, linings, hosiery, dresses, and shirts. Acrylic is able to absorb moisture up to only 3% of its own weight, evaporating it fast to the environment, making it not suited for people who emit lots of moisture. It is unable to hold air within its structure for heat insulation purposes; it accumulates static charge but is very elastic (elongation up to 55%) and has an antiallergic activity.

### 2.1.2.2.6 Polyester

Polyester is a manufactured fiber in which the fiber-forming substance is any long-chain synthetic polymer composed of at least 85% of an ester of dihydric alcohol and terephthalic acid. English chemists developed the first viable polyester fiber in 1941, and
it is now the most widely used fiber, even surpassing cotton. Polyester is strong and resistant to shrinking, stretching, creasing, insects, and most chemicals (Cook 1984). The fibers are smooth and silklike. The specific properties, however, vary significantly depending on the type of polyester fiber (Joseph 1986). Many are modified to increase flame, crush, or oil resistance. Polyester is primarily used in clothing and home furnishings. It is often blended with wool, cotton, rayon, or flax.

Like acrylic, polyester is not able to absorb moisture (up to only 0.4% of its own weight), making it unsuitable for people who emit lots of moisture. It is unable to hold air within its structure for heat insulation purposes, and it builds up static charge. On the other hand, it is very elastic (elongation up to 50%) and is resistant to insects and microorganisms. It also absorbs and holds oils.

2.1.2.2.7 Rayon

Rayon is a manufactured fiber composed of regenerated cellulose and was the first major commercial synthetic fiber. There are several primary fiber production methods for rayon (Cook 1984), which is used for woven and nonwoven fabrics, rubbers, felts, tire cords, and cellophane.

The fibers are smooth glass-like rods, and are easily stretchable (up to 40% elongation). Rayon doesn’t wrinkle, it is soft and moisture absorbent (up to 16% of its own weight) but not able to hold air within its structure for heat insulation purposes. Rayon is resistant to dry cleaning solvents and to most insects except silverfish, so it has relatively good antiallergic properties.

### TABLE 2.3 Mattress Top Layer Properties

<table>
<thead>
<tr>
<th></th>
<th>Elastic Properties</th>
<th>Fluid Absorption/Permeability</th>
<th>Heat Insulation</th>
<th>Antibacterial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wool</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>−</td>
</tr>
<tr>
<td>Silk</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Cotton</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td>Linen</td>
<td>−</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Acrylic</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Polyester</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Rayon</td>
<td>+</td>
<td>+</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Nylon</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
</tbody>
</table>

*Note: “−”=bad; “+”=good.*

insulation purposes. Rayon is resistant to dry cleaning solvents and to most insects except silverfish, so it has relatively good antiallergic properties.

2.1.2.2.8 Nylon

Nylon is a generic name for any manufactured fiber in which the fiber-forming substance is any long-chain synthetic polyamide having recurring amide groups (–NH–CO) as an
integral part of the polymer chain (Cook 1984). It first was made in the early 1930s (derived from coal) and is still a commonly used fiber. All nyons are strong, tough, elastic, and have high gloss. They are extruded through a spinneret and have a circular cross section. Nylon fibers are used for clothing, undergarments, linings, carpets, tire cords, conveyor belts, parachutes, hosiery, and brushes.

Nylon fibers have excellent dyeability and are twice as durable as cotton (Joseph 1986). They are nonabsorbent (moisture regain up to 5.0% of weight) and dry quickly, which results in a cool and clammy fabric. Nylon is resistant to insects and microorganisms.

2.1.2.2.9 Summary

Most top layers are textiles and are, therefore, 2D structures. As a result, most of these tissues (see Table 2.3) are not able to hold large quantities of air, which is needed for heat insulation. For this purpose a 3D structure is required, which is why heat insulation is determined by the mattress core rather than by the mattress top layer.

New materials and material combinations with different properties have been developed (e.g., for clothing purposes), but these have not been applied to bedding at present (to the knowledge of the authors).

2.1.2.3 Mattress Overlays

As stated before, the quality of a mattress (e.g., insulating or support qualities) stands or falls with the top layer of the mattress, because it acts as the interface between the bed and the human body. In some cases it is necessary

FIGURE 2.19 Viscoelastic foam comforter (left) and gel foam comforter (right).

to add an overlay on top of the mattress in order to improve certain properties (e.g., pressure distributing qualities). This feature is often used for hospital applications, where optimal pressure distribution is needed for patients who remain in bed for a long time, and for camping purposes, where it is used as a pad on firm ground.
2.1.2.3.2 Foam

Most foam overlays are relatively thin (5 to 8 cm) and consist of a thin layer of polyurethane foam, sometimes filled with a gel (see Figure 2.19). Viscoelastic foam (sometimes referred to as memory foam) is often used, which offers good pressure distribution as it disperses pressure evenly around bony prominences at hips and shoulders (see Figure 2.19). These viscoelastic foams were originally developed for NASA to alleviate the G-force stresses and pressure placed on astronauts. The disadvantage is that sagging occurs when the viscoelastic foam layer is too thick, or when it is used for the entire mattress core.

2.1.2.3.2 Fluidized

Next to foam overlays, most hospitals make use of (alternating) air overlays (e.g., for the treatment of patients with burn wounds). These systems contain airflow holes that allow air circulation throughout the unit, reducing heat build up and optimizing interfaced pressure, as illustrated in Figure 2.20.

![FIGURE 2.20 Fluidized overlays.](image)

2.1.2.3.2 Skins

In traditional societies (see Chapter 1) skins are often used as bed overlay. A freshly slaughtered hide contains about 65% water and 33% protein (Kuhn 1986). Small amounts of other materials, such as fats, carbohydrates, and minerals, are also present. Tanning chemically changes the skin and makes it resistant to putrefaction. To the knowledge of the authors, leather—which is processed from skin—is not used for bedding.

2.1.2.4 Mattress Supports

Generally, five kinds of support structures can be defined: rigid bases, board bases, spiral bases, box springs, and slat bases. In the Western world slats are becoming more and more common, resulting in increased research, development, and individualized variety for this kind of support. First, different support structures are illustrated. Second, how different kinds of supports can be combined with different mattress classes is explained.
2.1.2.4.1 Rigid Base

As discussed in Chapter 1, many sleepers in traditional societies (such as the Vietnamese) recline on a rigid surface, such as wooden platforms or the ground. These rigid bases have poor support and ventilation qualities, so they are often used in combination with a mattress or mat. It is extremely important to dry or air these mattresses in order to avoid mildew formation, since most rigid surfaces do not let any air or moisture through.

Sometimes a rigid base or floor is heated, such as the traditional Korean “ondol,” which is heated by a system of tubes built under the flooring, with a translucent yet durable paper on top of it. Early ondol systems were fueled by hot smoke from a wood fire; today the heat source is more likely to be oil or electric.

2.1.2.4.2 Board Base

A board base usually consists of a wooden frame on which perforated plates are mounted at both sides. This kind of mattress support has slightly better—but still poor—ventilation properties and is very firm. Consequently, it offers inferior support to the human spine, especially in combination with a firm mattress.

2.1.2.4.3 Slat Base

A slat base consists of a wooden or metal frame on which slats are fixed horizontally and perpendicularly to the cranio-caudal direction. These slats are fabricated in wood, plastic, or glass-fiber, as illustrated in Figure 2.21, and are usually fixed separately onto the frame, comparable to a plank that is cut in pieces. In some cases slats are able to bend and to cant, in order to improve the support qualities.

![FIGURE 2.21](image)

**FIGURE 2.21** Separate slat fixation (left) or slat suspension (right) on the base frame.
Wooden slats are usually layered and are mounted prestressed on the frame. The number of slats (14 up to 30) and their thickness vary depending on the manufacturer; sometimes diversified slats (e.g., with different thicknesses, radii, or stiffnesses) are combined in one single base to optimize general bending properties: heavier slats are used in the pelvic zone where more weight has to be carried; softer slats are applied in the shoulder zone to allow larger displacement. An additional effect can be obtained by controlling directly or indirectly the bending or displacement properties of the slats, such as by a mechanical link (a strip or clips linking several slats together, as can be seen in Figure 2.22) or by a hydraulic link, as is the case for the Impulse® sleep system.

Recently, mechanical properties were optimized by proper design of the suspension of the slats in the frame (Figure 2.23). Flexible slat supports made of rubber, plastic, or steel are now able to bend and to cant. Canting slats that are mounted in pairs allow better adjustment to the contours of the human body, especially in the case of a lateral position; this adjustment can be improved by adapting the height of the slat suspension. The main part of the flexibility now comes from the suspension, resulting in a mattress support bending in the middle, which is especially useful when placing two support structures next to each other for a double bed. When fiberglass slats are used, all the flexibility comes from the suspension (e.g., steel clips or rubber), guaranteeing the same elastic characteristics over the entire width. Steel suspension clips can be fabricated with different materials or geometrical
(fiberglass) on a steel suspension (right).

**FIGURE 2.24** A rope suspension (left) and a hydraulic suspension (right).

properties, which allows combining several clip classes (e.g., soft pelvic zone) to optimize the support qualities over the entire width.

Next to these more or less standard suspensions, slats can also be suspended in connection with each other, either mechanically (e.g., by means of a rope, see the left of Figure 2.24) or hydraulically (e.g., by a system of pistons; see the right of Figure 2.24). The advantage of these systems is that they follow the contours of the human body better; the disadvantage is that these systems will sag (as illustrated in Figure 2.14) when the range of slat movement is not limited, or when all body zones (e.g., shoulder and pelvis) are forced to move in connection with each other.

2.1.2.4.4 Spiral Base

A spiral bed base consists of a metal frame on which more or less than 400 springs are stretched and weaved into each other (see Figure 2.25). In the past, springs were stretched in the cranio-caudal direction (lengthwise), resulting in a large distance (2 m) to be spanned by the springs. In order to avoid sagging, springs currently are stretched perpendicularly to this direction (widthwise) by spanning only 1 m instead of 2 m. A spiral bed base has perfect ventilation properties and offers reasonable support qualities, especially when different body zones are equipped with an adapted spring tension.

**FIGURE 2.25** Close-up of a spiral bed base.
2.1.2.4.5 Stretched Fabric

Sometimes the mattress and support structure are combined in one system that can be easily transported. These systems are used for various purposes (e.g., camping cot for traveling or baby cot for children), and can be made of different materials (e.g., cotton or polyester). Another example is a hammock, of which two types can be defined: the first one (left of Figure 2.26) is a more Western version of a traditional hammock (right of Figure 2.26), which was—and still is—used in places where sleeping on the ground might imply dangers (e.g., in rain forest).

Most cots do not offer a good support of the back, but pressure distribution is reasonable and moisture transport is good when cotton is used. On a traditional type of hammock one can sleep in different body positions, where on most cots only a supine position is comfortable.

2.1.2.4.6 Box Springs

Box springs generally consist of the same components as a bi-conical spring mattress (see Section 2.1.2.1.3), but have different material properties that offer a much firmer support to serve as a mattress support structure. Bi-conical springs are linked and mounted vertically, as is the case in a bi-conical spring mattress, but they are mounted on a stiff wooden or metal base frame. The elastic foam on top and around the springs gives rise to the box springs being softer than other kinds of supports.

2.1.2.4.7 Tatami

A traditional tatami (see Figure 2.27) consists of the heri (the cloth of the tatami), the omote (made of tightly woven rush grass), and the doko (made
of compressed rice straw). In more Western versions an insulation board made of other materials, such as compressed wood chips or foam, replaces the rice straw. An original tatami has a fixed size (174×87 cm) and is traditionally combined with a futon (see Section 2.1.2.1.7).

2.1.2.5 Blankets and Sheets

The most important functions of blankets and sheets are heat insulation and moisture absorption and transport. Except for feathers and down (see infra), the same materials are used as those discussed in the mattress top layer section.

Feathers consist of a central, hollow quill. In the case of flight feathers, each side of the quill has a series of slender, closely spaced barbs that interlock to form a continuous flat surface. Plume feathers are less cohesive with unconnected barbs. Down feathers, obtained from young birds or the undergrowth of adult birds, are soft and lack barbs. Commercial down, usually obtained from ducks and waterfowl, is lightweight and resilient. When used as a filling, down provides insulation and loft. It is used in winter apparel, sleeping bags, bedding, and pillows. Trade regulation rules allow a garment to be labeled 100% down when it contains a minimum of 80% down. Most down is imported from China, Taiwan, Poland, and the rest of Eastern Europe.

2.1.2.6 Pillows

In order to support the cervical spine correctly, the pillow should also be designed properly (Roberts et al. 1994). In the case of a lateral position the entire spinal column should be a straight line when projected in a frontal plane. This objective can be reached both by correctly positioning and shaping deformable pillows (e.g., feather pillows) and by correctly designing less deformable structures (e.g., latex pillows).

Pillows filled with down and feathers are easy to shake, to support the head and the neck in a proper way; they also have a better moisture permeability than polyurethane pillows. Deformable head pillows can be filled with many more material types, including those that were described earlier in this chapter, such as cotton or kapok. The traditional Japanese pillow

![Figure 2.28](image_url)

**FIGURE 2.28** Optimal support of the cervical spine by a preshaped latex head cushion.
(makura), for example, is filled with red beans, or buckwheat chaff. Latex pillows offer good heat insulation and support qualities when conceived well. Sometimes they are preshaped in order to support the neck, as illustrated in Figure 2.28, but it can take some time (2 to 3 weeks) to get used to them because they are less deformable. One or more air chambers with an adjustable volume are sometimes added to improve the support in the neck area.

Pillows are not only used to support the head and the neck area; they are also often applied as a spacer between the legs or the arms to improve the alignment of the legs, hips, and back when sleeping in a lateral position (see Section 2.2.2).

2.1.2.7 Combination of Mattresses with Support Structures

2.1.2.7.1 Overview

When choosing an optimal combination of a mattress and support structure, several anthropometrical characteristics are relevant in order to make a correct combination of different sleep system qualities. Especially, support qualities should be measured or modeled adequately before assigning a mattress to a person. Only the most significant parameters are discussed here briefly; a detailed anthropometries-based description is elaborated throughout the following chapters. Further, not every mattress can be combined with any kind of support structure: both sound and unsound combinations will be reviewed.

Body weight is an objective criterion to determine whether a mattress has to be soft or firm: heavier persons need firmer support, but extreme properties should be avoided. When a person has a personal preference, support qualities should remain primordial, keeping in mind that it usually takes at least 2 weeks to get used to a new bed. People with perspiration or allergy problems should choose an adequate combination (e.g., spring mattress + slat support). People with pronounced contours (e.g., large shoulder or hip width) are helped with different comfort zones: pocket spring or latex mattresses are perfectly suited here, especially when people sleep in a lateral position. In spite of the fact that the mattress is responsible for 60 to 80% of the support, it can be improved significantly by using an adjusted base, such as a canting slat suspension combined with a latex mattress.

A board base or rigid base can be combined only with a spring mattress in order to avoid ventilation problems. The combination of a polyurethane or latex foam mattress with a board base can cause mildew formation. Combining a board base or rigid base with a foam mattress can, therefore, only be accepted as a temporary solution, e.g., in order to provide some extra support in case the existing bed base has a too large deformation. For the same reason—but to a lesser extent—a box spring is also best combined with a spring mattress.

A spiral base has no ventilation or stability problems and can be combined with any kind of mattress. Pocket spring mattresses combine especially well with a spiral base, because they need a stable foundation and evenly distributed support.

When combining a slat base with a spring mattress, the stability of the springs is the prime issue: slats should be wide enough (at least 4.5 cm), they should not be able to turn over, and their number should be sufficiently large (n ≥ 28). Combining a polyurethane
foam mattress or a bi-conical spring mattress with a fixed slat base results in a very firm sleep system. Pocket springs can be combined with a slat base if a stretchable layer on the slats prevents the springs from slipping through.

The good support qualities of a base consisting of pairs of canting slats are best expressed in combination with latex or highly elastic polyurethane foam mattresses. Latex is more supple than most polyurethane foams, which makes it more suited to be mixed with this type of base; twin slat bases with a canting and bending suspension are best combined with latex mattresses in order to make use of the entire slat flexibility. Firm polyurethane foam mattresses or bi-conical mattresses can also be combined with a base consisting of pairs of canting slats, but this is not advisable because of the rigidity of these mattresses. Pocket spring mattresses can be combined only with this type of base if a stretchable layer on the slats prevents the springs from slipping through, and if the number of slats is sufficiently large (n≥28).

The flexibility of the mattress is even more important in the case of an adjustable base (e.g., to permit reading in bed), so latex is the best option. A combination with polyurethane foam is possible but not advisable, and a combination with bi-conical springs is impossible, given its rigidity. The combination with pocket springs is only possible if an adjusted mattress cover is used, if the number of slats is sufficiently large (n≥28), and if the type of pocket spring mattress is sufficiently flexible as a whole.

2.1.2.7.2 Summary

The properties of combinations of mattresses with support structures are summarized in Table 2.4.

<table>
<thead>
<tr>
<th></th>
<th>PU foam</th>
<th>Latex Foam</th>
<th>Bi-Conical Spring</th>
<th>Pocket Spring</th>
</tr>
</thead>
<tbody>
<tr>
<td>Board base</td>
<td>--</td>
<td>--</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Boxspring</td>
<td>–</td>
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<td>+</td>
<td>+</td>
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<td>Spiral base</td>
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<td>Canting slats</td>
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<td>++</td>
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<td>+</td>
</tr>
<tr>
<td>Adjustable base</td>
<td>–</td>
<td>+</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

*Note:* “--” = impossible; “−” = unwise; “+” = possible; “++” = desirable.

2.1.2.8 Guidelines

Back-support qualities are of primary importance when assigning a sleep system to a healthy person. People with perspiration or allergy problems should choose adapted materials. By defining material properties correctly (springs, latex, polyurethane, etc.) one can obtain correct support qualities for different kinds of mattresses. By combining
different stiffness zones one can optimize support properties. Care should be taken in assigning a mattress with comfort zones to an individual; in principle, each person needs different zone subdivisions, so an incorrect assignment will do more harm than good. Finally, not every mattress can be combined with every kind of support structure.

2.2 Posture

Next to the influence of different types of support structures for the human body (see Section 2.1), the influence of different postures (Dolan et al. 1988) is an important determinant of the previously discussed physical factors (see Chapter 1). As stated before, optimizing body posture in both conscious and unconscious ways ensures continuous spine protection (Gracovetsky 1986). But instead of creating perfect conditions to allow optimizing our body position in an unconscious way, the sleep system actually forces us into a certain position. Body position is therefore limited to an initial conscious selection and subsequent unconscious optimization.

Furthermore, posture changes are necessary to avoid pressure overloading of soft tissues and to prevent muscle stiffness. During sleep a local ischemia—a deficiency of blood or oxygen supply—will arise in body zones that are in contact with the sleep system. This ischemia generates metabolic substances that stimulate the sensible nerve extremities, which will cause the person to change his/her posture before it gets painful (Dzvonik et al. 1986).

Most people have a preferred sleeping posture—frequently a fetal position—and change posture about 20 times a night. Timing is often dependent on the bed partner (Pankhurst and Horne 1994). Furthermore, the sleep locomotion system (which is the system that controls body motion) starts working, resulting in 65% of the people sleeping in a lateral position, 30% in a supine position, and the remaining 5% in a prone position. Sleeping postures are age related: older people usually have a preferred side to sleep on (especially on the right side). They rarely sleep in a prone position, sleep for a shorter time, and change their position less frequently (De Koninck et al. 1992).

These facts make it virtually impossible to define an overall ideal sleeping posture; different sleeping postures and how they influence back support are discussed next.

2.2.1 Prone Position

In spite of good distribution of body weight over a large contact surface, a prone sleep position is the most unfavorable posture in relation to back support, even on a sleep system with good support qualities. Gravity causes the heaviest middle part of the human body to sink deeper into the mattress while legs remain stretched. Consequently, lumbar lordosis will increase significantly and will augment the pressure on the facet joints at the posterior side (Twomey and Taylor 1983), while soft tissues (e.g., ligaments) will be under tension at the anterior side, as illustrated in Figure 2.29. This effect may result in a hyperlordosis on soft mattresses and some pressure-distributing sleep systems due to an increased mattress indentation in the pelvic zone.

When sleeping in a prone position, the combined effect of (1) the body weight resting on the rib cage and (2) the intestines being pressed against the diaphragm increases
pressure on the lungs, which may cause respiratory problems. Further, the head is usually
turned sideward to improve breathing, which increases neck rotation. Consequently,
increased spinal loading

![Increased lumbar lordosis when sleeping in a prone position.](image1)

**FIGURE 2.29** Increased lumbar lordosis when sleeping in a prone position.

![Improved back support in a prone position.](image2)

**FIGURE 2.30** Improved back support in a prone position.

occurs, because several facet joints of the most cranial vertebra are compressed at the
side to which the head is turned, while ligaments on the other side will be under tension.
Blood vessels may also be compressed causing headaches, dizziness, and other disorders.

In spite of all disadvantages—especially increased lumbar and cervical spinal
loading—many people prefer a prone position. It is, therefore, advisable to improve spine
support by simple means: sleeping without a pillow will reduce neck rotation, which can
be improved by putting a pillow under the shoulder and the rib cage at the side to which
the head is turned, or by lifting the arm at that side. Putting a pillow under the belly easily
restores the natural lumbar lordosis, as shown in Figure 2.30. The same smoothing of an
eventual hyperlordosis can be reached by elevating the knee and the hip at the side to
which the head is turned, which can be enhanced even more by placing a pillow under the
hip and the knee at this side. In fact, most of the cited corrections implement a slight
position shift to a lateral position.
2.2.2 Lateral Position

The lateral position is the most adopted sleeping posture, and it is able to support the human spine correctly when both the sleep system and pillow are well conceived: the spinal column is a straight line when projected in a frontal plane, while natural curves (cervical lordosis, thoracic kyphosis, and lumbar lordosis, see Chapter 1) are maintained. Flattening of the lumbar lordosis—as happens during unloading of the spine or during weightlessness—can be obtained by bending the knee and hip joint. Since this is not possible in any other position without a sophisticated mattress support, it is probably the main reason why people prefer this position. There are no differences between sleeping on the left or on the right side, except the weight of the liver working on the stomach and the lungs when sleeping on the left side.

![Correct lateral position](image1)

**FIGURE 2.31** Correct lateral position.

![Preshaped viscoelastic leg spacing](image2)

**FIGURE 2.32** Preshaped viscoelastic leg spacing.

Due to decreased contact surface and the center of gravity being more elevated, a lateral position is an unstable sleep position, which can be altered by the correct positioning of the extremities. Bending arms and legs enlarges the support area and thus improves stability (see Figure 2.31), but care should be taken not to apply torsion on the spine, to which intervertebral disks are especially vulnerable; when turned about a longitudinal axis, both pelvic and shoulder girdle should adopt the same angle.

The use of pillows can be an easy solution for the prevention of torsion of both the pelvic and shoulder girdles; putting a pillow, blanket, or preshaped pillow between the knees as a spacer will stabilize the most elevated leg in a horizontal position, as illustrated Figure 2.32. This position also avoids an asymmetric loading of the spine,
which might induce scoliosis. A similar effect can be reached by putting a pillow between the elbows. Due to the fact that the human body will strive for minimal loading while sleeping, most people will automatically adjust their position or use a blanket or cushion in order to improve the alignment of the legs, hips, and back when sleeping in a lateral position to obtain the previously described minimal loading of the spine.

In order to avoid any asymmetric loading of the spine, it is important that the feet are positioned higher that the pelvis, as illustrated in Figure 2.33.

People—and muscles—are relaxed when sleeping in a fetal position; upper legs and trunk should form an angle of 135° to avoid a hyperlordosis (when stretching legs) or a smoothed lordosis (when elevating the knees too close to the trunk). Further, it is clear that people with major spinal disorders (e.g., people with a spinal injury) need special treatment; a moderate spine torsion or flexion may yield stress relief at the level of injury, implying only a temporary solution because the spinal column will suffer increased loading at other places.

2.2.3 Supine Position

The main advantage of sleeping in a supine position is the fact that body weight is distributed over a large surface, resulting in pressure distribution and stability being optimized. The lumbar part of the vertebral column will mostly be positioned between a smoothed lordosis and a slight kyphosis, depending on (1) the kind of sleep system, (2) the natural curves of the spine, and (3) muscle tension while sleeping.

When a sleep system is too soft, places where body weight is concentrated (e.g., the hip zone) will sink deeply into the mattress. Some muscles may be well relaxed in this position, but the spine certainly will not; the pelvis will cant backward resulting in a complete and unnatural lumbar kyphosis. At the anterior side intervertebral disks will be compressed while soft tissues (e.g., ligaments) will be under tension at the posterior side.

When a sleep system is too firm, the lumbar part of the vertebral column will not smoothen immediately when lying down (see Figure 2.34 a), and no contact will be made between the lumbar part of the back and the mattress. Upon muscle relaxation (which occurs after 10 to 15 minutes on average) the pelvis will cant backward slightly, which results in a slight smoothing of the lumbar part of the vertebral column (see Figure 2.34 b). Some persons might however experience discomfort due to muscle tension that arises.
when the pelvis cant backward while the legs stay in a horizontal position. A semi-Fowler’s position may solve this problem (see further) but requires an adjustable bed.

In order to support the natural cervical lordosis it is best to use a pillow, although it is less obligatory compared to a lateral position. Furthermore,

![Figure 2.34](image1.png)  
**FIGURE 2.34** Supine position on a firm surface.

![Figure 2.35](image2.png)  
**FIGURE 2.35** Semi-Fowler’s position on an adjustable bed.

people with respiration problems should avoid sleeping in a supine position, as apnea (Cartwright 2001, Cartwright et al. 1991) and snoring frequency are much higher in this posture (see Section 1.2.1.3). It would lead too far from the core of the subject to discuss here how posture should be adjusted in case of low back pain, neck problems, or muscle stiffness. Only the semi-Fowler’s position will be mentioned here (Figure 2.34), being a common relaxed posture for many patients. It can be adopted in the case of an adjustable bed: both hip and knee joints have an angle of 45°, resulting in a relaxed iliopsoas muscle (i.e., the great flexor muscle of the hip joint, divisible into two parts, the iliac and great psoas) and a slightly smoothed lumbar lordosis. Changing posture is, however, difficult in this position because of the fixed setup of the bed. It is remarkable that astronauts experience more or less the same posture, and that most people sleeping in a lateral position automatically try to attain a similar position.
2.2.4 Guidelines

A reliable sleeping posture evaluation can be made based only on invariant shape properties of the spine, such as preservation of lumbar lordosis. In a correct sleeping posture the human spine adopts its natural position, which is assumed to be the same as it takes in the upright position, yet slightly smoothed by the fact that, in a sleep position, the direction of the gravitation vector no longer coincides with the cranio-caudal direction of the body. Because the human body will strive for minimal loading while sleeping, most people will automatically adjust their posture to their sleep system.

It is nearly possible to obtain correct back support in a prone sleep position. In the case where a person has no health complaints (respiratory or back problems), lateral and supine positions are equivalent. Sleeping in a correct posture, however, does not guarantee a good night’s sleep; freedom of movement in order to change posture is also important. Unfortunately, some types of sleep systems are intended for other uses as well (e.g., a sitting couch or an airplane seat), which results in reasonable support of the spine in some positions (e.g., supine position), but the inability to change to other positions. Airplane seats can offer good support in a semirecumbent supine position (e.g., in a semi-Fowler’s setting), but changing to a lateral position (which is preferred by most Western people) is potentially hurtful unless the seat or mattress can be fully stretched out at 180°.

Finally, when changing a sleep system it usually takes 2 weeks to get used to it. Temporarily worse back support on a new and better sleep system is possible.

2.3 Conclusion

This chapter discussed the underlying determinants—including the influence of different types of body support and different postures—of the physical ergonomic properties that were illustrated in the first chapter, concentrating on back-support qualities that are of primary importance when assigning a sleep system to a healthy person. Body posture is directly connected to spine protection, since optimizing body posture ensures continuous spine deformation minimization. Actual sleep systems, however, force us in a certain position, thus enlarging their role in spine support by limiting body position to an initial conscious selection and subsequent unconscious optimization.

Consequently, the design of sleep systems (and the correct assignment to different population classes) is of primary importance at the moment. By defining material properties correctly (springs, latex, polyurethane, etc.) one can obtain correct support qualities for different kinds of mattresses. By combining different stiffness zones one can optimize support properties. Efforts should, however, be made in the future to achieve perfect sleeping conditions and to create freedom of movement by trying out new concepts of sleeping.

References


3

How to Measure Spinal Alignment

People spend a large part of their life in bed during which they are not able to control their body position in an active and conscious way. Chapter 1 reviewed the most important ergonomic factors affecting the quality of sleep, including physical, physiological, and psychological ergonomic parameters, and Chapter 2 focused on the underlying determinants of the physical factors: the properties of different sleep systems (mattress + support structure + pillow) and the characteristics of different sleeping postures. In conclusion, a bed has to be appropriate for different sleeping postures and has to fulfill many requirements depending on personal needs.

When ranking these physical factors, it is widely believed that, for normal healthy people, the basic task of a sleep system is to correctly support the spine, since low back pain is often related to incorrect support of the body. Secondary physical parameters, such as pressure distribution or heat insulation, should not be optimized, but also not neglected.

This chapter discusses the consequent need for an objective and scientifically sound method to determine the right sleep system for each individual, optimizing spinal alignment. Important in this definition process—as defined on the flowchart in Figure 3.1—are new experiments, both virtual and actual, to evaluate spinal alignment during bedrest by comparing the spine position on a sleep system with the spine position during upright standing.

The first section of this chapter discusses and compares assessment techniques that are appropriate for this kind of measurement. The second section describes two experimental setups that are actually designed and built to measure the spine during bedrest in order to evaluate back support qualities. In the first stage a two-dimensional technique is conceived: for a lateral position, reflecting markers are mounted on the spinous processes and detected by a camera system; for a supine position, a similar system assesses the mattress surface by measuring the vertical displacement of pins that are pierced through the mattress.

In reality, people do not limit themselves to these two-dimensional sleep positions, which makes the expansion to three-dimensional measurements a logical next step. In a second stage, white-light raster line triangulation hardware and active contour software are applied to evaluate the spine in 3D.
3.1 Which Measurement Techniques Are Able to Evaluate the Spine?

This section analyzes and compares different measurement techniques that are able to define the shape of the human spine when lying on a sleep system. The first subsection describes the properties the ideal equipment should have, the second subsection depicts and analyzes different measurement techniques that meet these requirements to some extent, and the third and last subsection evaluates each of the techniques individually and comparatively. Based on this assessment it is possible to decide which equipment is most suitable for two-dimensional and three-dimensional measurements, respectively, of the vertebral column.

3.1.1 Desirable Measurement Technique Properties

3.1.1.1 Complete Depiction of the Spine

Given that vertebral shapes and sizes are described extensively in literature—at least for healthy adult people—a required and sufficient data set depicting the spine consists of (1) the three-dimensional positions of the centers of all vertebral bodies and (2) the orientation of each individual vertebra. Intervertebral disk load can be derived from these details to predict mechanical back pain. A solid measurement technique should therefore be able to gather these data.

If necessary, vertebral rotation can be limited to axial rotation only, because it is possible to estimate the two other rotations from the three-dimensional curvature of the spinal midline, which is the line through the centers of the vertebral bodies.

3.1.1.2 Accurate Depiction of the Spine

First, the vertebral column should be measured in a relaxed state. Given that some techniques might require actions taken by the subject—and therefore only operate during alertness—a relaxation period of at least 15 minutes before measuring is mandatory.
Second, the actual shape of the spine should be depicted accurately in order to estimate intervertebral disk loads in a sound way (Colombini et al. 1985). Lateral deviations from the correct position of the vertebral column should not exceed 5 mm in a frontal projection.

Finally, the resulting three-dimensional shape of the spine should be independent from the position and orientation of the person with respect to the equipment.

3.1.1.3 Correct Depiction of the Spine

External measurement techniques first locate the spinous processes starting from the skin surface and then estimate the distance from the spinous processes to the centers of the vertebral bodies. Literature, however, only partially describes thickness values of the intermediate layer (consisting of muscles, ligaments, and other soft tissues) between the processes and the skin. Furthermore, only limited information about the distance to the centers of the vertebral bodies is available, and the position of this center is additionally disturbed by a poor correlation between the axial vertebral rotation and the rotation visible at the surface. Therefore, measurement techniques that visualize the internal shape of the vertebral column generally yield more reliable results than external techniques.

3.1.1.4 Limited Body Contact

If touched, a sleeping person will not be relaxed, resulting in the vertebral column deforming less in comparison to a completely relaxed situation as during sleep. Contact, therefore, should be avoided—or at least limited—because it will influence posture.

3.1.1.5 Limited Operator Interaction

An objective diagnosis is only possible when operator interaction is limited for both the measuring phase (e.g., attaching markers to the body) and the analyzing phase (e.g., image interpretation). Manual interaction should be avoided, and image analyses should be included in computer algorithms as much as possible. This automation is largely dependent on the type of measuring technique and the complexity of the subsequent analysis.

3.1.1.6 Limited Measuring Time

Small posture changes at some stage in the measurement may cause the image to become unclear—as with prolonged closing time of a camera diaphragm—so exposures should be instantaneous. Furthermore, measurement analyses should be fast in order to evaluate a large number of persons and sleep systems. It is clear that both digitalization and automation reduce the assessment time considerably. In conclusion, both measurement time and analyzing time should be as short as possible.
3.1.7 Limited Cost

As with all equipment, the cost involved should be limited in order to make a rational initial investment and to enable a possible future commercialization. The equipment should be able to perform at reasonable operating costs in order to be available to the general public.

3.1.8 Flexibility

A comparison between the spine position on a sleep system and the spine position during upright standing can be a good evaluation of body support on a sleep system. The ability to measure the spine in both upright and lying positions is a strong advantage of the equipment. Furthermore, it is clear that a measurement technique should be able to assess as many sleep positions as possible (lateral, prone, supine, etc.).

3.1.9 No Detrimental Effects

Measurement techniques that have detrimental effects on health are preferably not used on a large scale, since the safety of the persons being tested is of primary concern.

3.1.2 Which Measurement Techniques Meet These Requirements to Some Extent?

This section analyzes different techniques that might be considered to measure the shape of the spine. They are subdivided into three categories (Gilio and Reynders 1998): techniques that are used to analyze or visualize bone or soft tissues (X-rays, ultrasound, MRI-scans, CT-scans, EMG, etc.), techniques used to detect a spinal deformation (thermographs, moiré-topography, white-light raster line triangulation, three-dimensional marker tracking, goniometrical instruments, etc.) and techniques used to reconstruct three-dimensional images such as optic holography.

3.1.2.1 X-Rays

3.1.2.1.1 Description

On a roentgenogram the vertebral column is clearly visible simply because X-rays are absorbed extensively by bone. X-rays strongly diverge, so when the patient is positioned between the X-ray machine and the film—as is the case with a planar radiograph—he/she should be positioned as close as possible to the film to obtain a realistic projection of the body’s dimensions. The axial rotation of a vertebra can be derived from a planar radiograph.
Stereo radiograph of a tibia/fibula. 

(Stokes et al. 1986), mostly a sagittal or frontal spine projection (see Section 1.1.1.1 for the anatomy of the spine), using the method of Nash and Moe. The distances of both pedicles with respect to the center of the vertebral body are measured in a plane that is perpendicular to the roentgenogram, and the difference between them reflects the axial rotation. These distances are, however, strongly dependent on the shape of the vertebral body and the distance from the vertebral arch to the vertebral body. The axial rotation of the vertebrae can, therefore, be obtained more accurately from a bi-planar radiograph (Selvik 1990) (consisting of a sagittal and a frontal projection of the spine) or from a stereo radiograph (consisting of two exposures with an arbitrary but fixed position with respect to each other, as shown in Figure 3.2).

Tomography is a radiological method used to erase the confusing shades covering regular radiographs. Computerized tomography (CT-scan) depicts an undistorted image of a transversal cross section of the vertebral column by scanning the person with a fan-shaped bundle of X-rays turning over 180°. Opposite to these X-ray sources, a chain of detectors (consisting of crystals that convert roentgen quanta to light) measure roentgen photons that are not absorbed by the human body. A computer further depicts each transversal cross section in a relatively accurate way, as shown in Figure 3.3, and with good repeatability. This technique is therefore well suited to assess the accuracy of other techniques.
3.1.2.1.2 Evaluation

X-ray-related measurement techniques depict an internal image of the spine in any posture and do not make contact with the person. They have a brief measuring time and—in spite of the fact that no extensive experience is needed to evaluate the images—they require a long analyzing period due to the digitalization process. Regular X-rays are not suited to measure the spine on a sleep system because the image is dependent on the position and the orientation of the person with respect to the equipment and because image digitalization is completed manually. Bi-planar radiography, stereo radiography, and tomography are able to measure accurately and independently the three-dimensional position, orientation, and shape of each vertebra from the position of the person with respect to the equipment. Both roentgen equipment and low-end scanner equipment (with manual digitization) can have a relatively low cost (from $25,000) depending on the type of system.

Unfortunately, X-ray-related measurement techniques have a detrimental effect on health: the high-energy radiation can damage tissues and initiate leukemia or breast cancer. A lead shield should, therefore, protect sensitive organs, and each exposure has to take place under the supervision of a radiation physicist. Since the effect of radiation is accumulated, the technique is not suited to do large-scale measurements (e.g., to measure one particular person on 10 different sleep systems).

3.1.2.2 Ultrasound

3.1.2.2.1 Description

A transmitter making contact with the skin is able to produce ultrasound waves; these waves penetrate the body and are reflected at each structural transition (Wells 1969), defining the inner structures of the human body. The intensity of the reflected wave depends on the acoustic impedance of the structures involved. At a bone-soft tissue transition almost total reflection occurs, resulting in the bone being silhouetted white on a two-dimensional cross section (B-scan), as can be seen in Figure 3.4. The other underlying structures will not be visible anymore, since they are lying in the “shade”

![FIGURE 3.4 Ultrasound detection of two transversal processes.](image-url)
of the bone. In addition to reflection, the intensity is also weakened by wave propagation, since wave energy is converted to warmth. This effect—called wave attenuation—will grow in proportion to the distance from transmitter to receiver. A pulsating transducer acting as transmitter and receiver can be used for a simple control of the operations.

Generally, ultrasound is used to visualize soft tissues, so only a limited number of applications tracing the vertebral column were found in literature. One measures the diameter of the vertebral canal with a 1.5 MHz transducer (Ledsome et al. 1996). Another measures distances between consecutive transversal processes with a 2.5 MHz transducer (Letts et al. 1988). In both cases, transducers are rotated manually until the image is sharp before taking a scan, resulting in an absolute inter- and intra-observer error of 0.002 meters and a relative error of 3.5%.

By moving a two-dimensional array transducer over the skin surface, a three-dimensional reconstruction of the two-dimensional scans can be made by a computer if the position and the orientation of the transducer are known at any moment. Two similar three-dimensional ultrasound systems were evaluated in the framework of this study: (1) a 3D Voluson (Kretztechnik) with a 5 MHz transducer and (2) a Siemens scanner at U.Z. Gasthuisberg (KULeuven) with 7- and 10-MHz transducers, respectively. The spinous processes are easy to trace at 7 MHz, being silhouetted white against a black underlying structure. Given that axial rotation of the vertebra should be calculated starting from the relative positions of the end points of the transversal processes, other bony tissues should be measured, too, but both the transversal processes and the posterior contour of the vertebra are difficult to trace because the image is full of white spots.

There are several phenomena explaining the difficulty of imaging the posterior contour of the vertebra. First, a wave will not be reflected to the receiver when it runs into a surface that is not perpendicular to the direction of propagation. Second, at each structural transition reflection will occur, resulting in white spots. Finally, a wave may also reflect on the inner skin surface, and it is possible that this wave is received only after several movements between the inner skin and the bone, explaining white spots on a longer distance than the spinous processes. Further, a lot of manual interaction and operator experience is needed to trace even the spinous processes; digital signal processing (e.g., use of wavelets) might be a solution (Harris and Wells 1993; Solbakken and Sommerland 2003).

Additional problems are the uncertainty about medium density, the choice of an appropriate wave frequency, and data management. Since the distance between the skin and the bone is calculated from reflection time and wave velocity, the distance estimation depends on the density of several media (blood vessels, ligaments, nerves, etc.) and therefore cannot be defined accurately. Waves with a high frequency will weaken more than low-frequency waves, but they offer a better contrast. Therefore, a multi-frequency transducer is needed in order to picture both spinous and transversal processes. Finally, a two-dimensional transducer is not wide enough to picture all vertebral processes, and scanning memory is limited, resulting in a scanning process consisting of several stages and requiring a lot of processing time. If the person being tested moves during this process—which is likely to happen because of the contact—an inadequate picture of the vertebral column will be obtained.

In literature, ultrasound holography (Baum 1975) is described as a promising scanning technique offering a better three-dimensional resolution because it measures both wave
amplitude and phase. However, at the moment of writing, this technique has only been developed to a preliminary stage.

3.1.2.2 Evaluation

Ultrasound waves are able to visualize the inner structures of the human body accurately and without detrimental effects. Three-dimensional ultrasound equipment can picture the three-dimensional position, orientation, and shape of each vertebra independent from the position of the person with respect to the equipment. Operator intervention, however, limits the applicability since (1) the transducer should be positioned and oriented correctly with respect to the skin surface, and (2) a considerable amount of interpretation experience and manual interaction is required to trace bone reflections. Consequently, both measurement time and analysis time are extensive. Other limiting factors include the contact with the test person, the restricted number of possible postures that can be measured, and the cost price ($90,000 for three-dimensional equipment).

3.1.2.3 Magnetic Resonance Imaging

3.1.2.3.1 Description

Magnetic Resonance Imaging (MRI) is a technique that visualizes soft tissue based on the observable fact of absorption and emission of electromagnetic radiation by the atomic nucleus of hydrogen. In spite of the low hydrogen content of bony structures, MRI can visualize bone thanks to the sharp contrast with the surrounding soft tissue, resulting in a black and white photo-like image as shown in Figure 3.5. The magnetic field—generated by superconducting coils—should be constant, uniform, and relatively high (generally varying between 0.15 and 4 Tesla) to improve the contrast. Expensive liquid helium cooling is therefore needed to obtain the critical temperature for superconductivity.

FIGURE 3.5 MRI scan of the lumbar vertebral column.

Most MRI machines have the shape of a tunnel (diameter 0.4 m) through which the human body is moved horizontally. Posture changes and even breathing may disturb MRI, since a recording takes a few minutes. An iterative algorithm can, however, reduce these artifacts—and consequently improve the image quality—by feeding back the person’s movements to the captured images. This method is able to improve the image quality on the precondition that the time intervals of moving (e.g., breathing) can be traced accurately.
Boos (Boos et al. 1996) proposes an indirect approach—the so-called “centroid” method—to measure the spinal curvature based on an MRI: points are defined alongside the outline of a sagittal cross section of each vertebral body, and the centroid of the contour through these points estimates the vertebral body center. The curve that joins the centroids approximates the one through the centers of the vertebral bodies.

3.1.2.3.2 Evaluation

Magnetic resonance imaging is an accurate technique to visualize the three-dimensional position, orientation, and shape of each vertebra independently from the position of the person with respect to the equipment (Atlas 1991; Boos and Boesch 1995). No contact with the body is made, and there are no detrimental effects. Measurement time and analysis time are, however, extensive, mainly due to image capturing and manual interaction, respectively. Other limiting factors include the cost ($1,000,000–2,000,000) (Bell 1996) and the restricted number of possible postures (no upright position) and sleep systems (no metal parts, no mattresses wider than 0.4 m) that can be measured.

3.1.2.4 Surface Electromyography

3.1.2.4.1 Description

Electromyography (EMG), and more specifically surface electromyography (SEMG), are techniques that measure muscle response to nervous stimulation, expressed in the electrical activity within muscle fibers. For SEMG a needle electrode is inserted through the skin into the muscle; for EMG an electrode is implanted in the muscle. The electrical activity detected by the electrode(s) is displayed on an oscilloscope and may be displayed on a computer screen, as illustrated in Figure 3.6. Each muscle fiber that contracts will produce an action potential, and the size of the muscle fiber affects the rate (frequency) and size (amplitude) of the action potentials. The presence, size, and shape of the resulting waveform produced on the oscilloscope will provide information about the muscle activity. Because skeletal muscles are isolated and often large units, each electrode gives only an average picture of the activity of the selected muscle. Several electrodes may need to be placed at various locations to obtain an accurate study. Furthermore, EMG signals typically consist of several transient components, which are interesting to isolate and classify according to their physiological significance. These signals contain information on which muscle groups have been activated and are measured in microvolts (RMS).

At rest, muscle tissue is normally electrically silent. Once the insertion activity (caused by the trauma of needle insertion) quiets down, there should be no action potential on the oscilloscope. When the muscle is voluntarily contracted, action potentials begin to appear. As contraction is increased, more and more muscle fibers produce action potentials until a disorderly group of action potentials of varying rates and amplitudes (complete recruitment and interference pattern) appears with full contraction.
FIGURE 3.6 EMG measurement of lower back muscles.

There are systems commercially available—such as the Back-Up® measuring system—that evaluate spinal alignment by measuring EMG signals. These systems presuppose that muscle activity needs to be minimized during sleep in order to optimize body support (and spinal alignment). In order to evaluate this, a set of electrodes is placed on the skin over the lumbar fibers of the musculus longissimus thoracis (in the middle of the line of communication between the interspinal space of L1 and L2, and the spina iliaca posterior superior, see Figure 3.6) to detect the electrical signals associated with muscle contraction. By measuring and analyzing EMG signals on different sleep systems, a prediction can be made of which system offers the best support qualities.

3.1.2.4.2 Evaluation

SEMG analyzes the spine in a quantitative and nondetrimental way by measuring muscle activity. SEMG measurements are independent from the position of the person with respect to the equipment, and measurement time is short. On the other side, contact with the body is made, and the positioning of the electrodes and the interpretation of the measurements need expert intervention. The cost can be relatively low ($5000–40,000) depending on the type of system, but the big question, however, is the relevance of SEMG: is it possible to quantify spinal alignment by SEMG?

On one hand, there are some factors that indicate a relation between musculoskeletal impairment of the lower back and SEMG. Experiments (Roy et al. 1995) have concluded that muscle impairments in patients with low-back pain disorders can be distinguished from normal muscle functioning in subjects without low back pain with a 90% accuracy based solely on median frequency parameters.

On the other hand, it is not possible to characterize a three-dimensional line through the vertebra in an objective and quantitative way by SEMG, at least not at present, although literature (Lahm and Iaizzo 2002) confirms that no clear relation between spinal alignment and SEMG has been distinguished so far. Furthermore, even if there is a relation, it would not be reciprocal, as one can easily imagine situations in which the human body is not supported correctly (e.g., sitting on a chair with legs supported only at the heels) while muscle activity is low.
3.1.2.5 Geometrical Instruments

3.1.2.5.1 Description
This category of instruments touches the back’s surface while registering the point(s) of contact electronically. For example, a force-controlled robot could trace a back’s surface autonomously, but high safety demands would make it an expensive alternative. A workable solution is the Metrecom Skeletal Analysis System by Faro Medical Technologies, which consists of a serial connection of rods and potentiometers. The far end of the arm is positioned manually on the spinous processes by the examiner, and the three-dimensional positions of the measured points are automatically transferred to a so-called “point cloud” describing the back’s surface, as can be seen in Figure 3.7. A lordosimeter or inclinometer can be considered as a simplified version of this category of equipment.

The shape of the spine can also be “copied” by placing a deformable apparatus on the back’s surface (Gross et al. 1982). A typical example is the foldable rail used by physiotherapists; it is placed against the back’s surface and adopts the shape of the line through the spinous processes. Electrogoniometers (Boocock et al. 1994) or strain gauges measure the deformation of the rail. Continuous systems generally offer a better solution than devices consisting of a chain connection of independent parts. The large number of links needed to measure the relative motion between the consecutive points of the chain (six degrees of freedom for each connection) make it difficult to design a mechanical device that measures the relative position and orientation of each of the vertebra. In addition, the complexity of this kind of apparatus might influence the test person’s posture.

3.1.2.5.2 Evaluation
Geometric instruments are able to measure an external three-dimensional line through palpated spinous processes without any detrimental effects. Palpation is a method of examination in which the examiner feels the location of an underlying structure by pressing on the surface of the body. Making contact with the sleeping person will however cause him/her not to be relaxed, resulting in a different spinal curvature.
compared to a completely relaxed situation. The evaluation is independent from the position of the person with respect to the equipment, but no information about the axial rotation of the vertebra is produced. Measurement time is long due to the palpation procedure; analysis time is short because digitized procedures are used. Further, the palpation process requires a lot of experience and involves a relatively large absolute error (±5 mm). In addition to this error, the sensors or sources might shift with respect to the skeleton in case the person moves (Mior et al. 1996). The cost is relatively low ($2000–10,000), and no further adjustments are required for measuring persons while lying on a sleep system.

### 3.1.2.6 Three-Dimensional Tracking

#### 3.1.2.6.1 Description

This category of instruments is able to evaluate the back’s surface by registering the position and orientation of several anatomical landmarks. Sensors, sources, or markers are placed on the processi spinosi or other anatomical landmarks (after palpation) to be captured electromagnetically (McGill 1997), acoustically, or optically (Dawson et al. 1993).

**3.1.2.6.1.1 Electromagnetism**—The Isotrak® system from Polhemus is a magnetic device that defines the orientation and position of different vertebrae with respect to the sacrum. It consists of a magnetic source (three perpendicular coils emitting a low-frequency field) attached to the sacrum, and magnetic sensors (also consisting of three perpendicular coils) attached to the spinous processes.

**3.1.2.6.1.2 Acoustics**—In the case of acoustical measurements, a source is positioned on each spinous process and emits an acoustical signal that is captured by three independent microphones. The three-dimensional position of each process can be calculated from the transmission times; the vertebral rotation also can be measured by placing three sources on each spinous process. Cobb angles (which are used to quantify scoliosis of the spine) larger than 30° can be detected well—as described in literature—but when the Cobb angle is smaller than 30°, the curve will be smoothened.

![FIGURE 3.8 MAC-Reflex three-dimensional optical tracking system.](image)
3.1.2.6.1.3 Optics—The processi spinosi are palpated and indicated by spherical markers that are able to reflect ultraviolet or infrared light. A (digital) camera captures the entire back’s surface and registers the positions of the processi spinosi. A computer then analyzes the digitized images and reconstructs the marker positions in two dimensions (e.g., the frontal plane). When several cameras are used to trace the markers, a three-dimensional curve depicting the spinous process positions can be constructed. This kind of equipment is used mostly for (human) motion analysis by coupling the measurement data to anatomical models (see Figure 3.8).

3.1.2.6.2 Evaluation

Three-dimensional tracking systems are able to measure an external three-dimensional line through the palpated processi spinosi without any detrimental effects. Contact with the body is made while attaching the markers or sensors but not during the actual measurement. The evaluation is independent from the position of the person with respect to the equipment, but information about the axial rotation of the vertebrae is not always produced. Measurement time is long, due to the palpation procedure prior to the marker attachment; analysis time is short, since it is digitized. The palpation process requires experience and involves a relatively large absolute error (±5 mm). In addition to this error, the sensors, markers, or sources might shift with respect to the skeleton when the person moves. No further adjustments are required for measuring people while they are lying on a sleep system. The cost is approximately $20,000.

3.1.2.7 Thermography

3.1.2.7.1 Description

Each object with a temperature above 0 Kelvin emits electromagnetic radiation that can be captured by an infrared detector. This detector is cooled

![FIGURE 3.9 Thermographical image of a person in a lateral position (object distance: 2.0 m; environment)](image-url)
temperature: 20.0°C; MERA BENELUX).

by liquid nitrogen and provides an outgoing voltage in proportion to the incoming radiation. Converting this voltage to a video signal results in a thermograph representing different temperatures with different colors. Figure 3.9 shows an image made by a Jenoptic Varioscan 3011 with a thermal resolution of 0.03°C.

The technique is not detrimental, since there is no radiation or energy flow to the human body. A thermograph can, therefore, provide an innocuous diagnosis for rheumatological, orthopedic, diabetic, dermatological, or blood vessel diseases or for the progress of wound healing. Depending on the syndrome, the injured tissue is warmer or cooler in comparison to the surrounding tissue. This is caused by the use of medication or by the disease or injury itself. Also, a scoliosis can be prediagnosed by a thermograph since the radiated temperature will be divided asymmetrically over the back’s surface. Only persons with a scoliotic or doubtful diagnosis have to be examined by X-rays. In addition, posture is not influenced by the measurements since no contact with the person being tested is made.

It might be expected that the presence of transversal and spinous processes would result in traceable temperature differences at the back’s surface. Tracking individual vertebrae remains difficult, however, since muscles and ligaments are attached to these processi and spread out over a large area, distributing the temperatures more equally and blurring a potentially sharp and accurate picture of the vertebral column.

3.1.2.7.2 Evaluation

A thermography visualizes the spine in a quantitative and nondetrimental way by measuring the surface temperature in two dimensions (Cooke et al. 1980). The evaluation is independent from the position of the person with respect to the equipment, and no contact with the body is made. It is, however, not (yet) possible to obtain a three-dimensional line through the processi spinosi or vertebra in an objective and quantitative way, and consequently no information about vertebral rotations is produced. Both measurement time and analysis time are short, thanks to the digitization process. The cost is about $35,000.

3.1.2.8 Moiré Topography

3.1.2.8.1 Description

Interference patterns arise when two periodic structures are superimposed on each other with a small angle difference. These patterns provide information on the surface they are projected on and can be constructed in two possible ways.

For shadow-Moiré, a grid consisting of equidistant line is positioned close to the (back’s) surface and projected on it by a source of light; a camera—positioned at a small angle with respect to the light source—captures the interference pattern of the real grid and the projected (shadow) grid on the surface. For each point in space, the intersection
of the camera projection line and the source projection line defines the level of profundity with respect to the (real) grid. Contours, called interference lines, appear when the back’s surface crosses these levels of profundity, as can be seen in Figure 3.10. No contact to the surface is made, but only the external part is evaluated, requiring additional algorithms to provide an analysis of the interior part (e.g., the vertebral column).

For projection-Moiré, a grid inside the projector is projected on the back’s surface. A reference grid—representing the projection of the first grid on a (flat) reference surface—is situated in the focal plane of the camera. The combination of the two grids results in a contour interference pattern indicating different levels of profundity of the back’s surface, as is the case for shadow-Moiré.

Profundity differences on the order of magnitude of 1 mm can be visualized when the camera resolution and the grid density are high enough, and when the subject is positioned close enough to the grid, since there is a nonlinear relation between the distance to the grid and the number of contours on the (back’s) surface.


A scoliosis is characterized by an asymmetrical topography at the surface level, so Moiré topography is able to detect it. Consequently, the number of proximo-distal interference lines in a transversal cross section will be different between the left and right parts of the back surface. This difference is proportional to the Cobb angle, but the numerical factor depends on the distance of the subject to the equipment and on the resolution. Since no automatic processing is available so far, topography has to be digitized or analyzed manually, requiring time and experience.

### 3.1.2.8.2 Evaluation

Moiré topography is able to visualize the back’s surface in an accurate way, without detrimental effects, and without making contact with the human body (Denton et al. 1992). Evaluation depends on the position of the subject with respect to the equipment, which can be corrected mathematically (Turner-Smith et al. 1988). Measurement time is short, but no automatic processing is available so far. Consequently, operator intervention
limits the practicability, since a considerable amount of interpretation experience and manual interaction is required to quantify surface properties. Other limiting factors include the restricted postures that can be measured (no supine position) and the fact that an extra algorithm is needed to evaluate the vertebral column, since no direct information about the position and the rotation of the vertebrae is produced. No further adjustments are required for measuring persons while lying on a sleep system. The cost is approximately $10,000.

3.1.2.9 White-Light Raster Line Triangulation

3.1.2.9.1 Description

White-light raster line triangulation (WLRT) is an analysis method for the assessment of three-dimensional objects using a line raster slide and a camera. This measurement technique is able to scan any three-dimensional surface by projecting raster lines on the surface and by capturing these lines under a known and fixed angle. The measured surface can be reconstructed mathematically by fitting a dense point cloud, based on triangulation algorithms. Frobin and Hierholzer (1982) have developed hardware and image processing techniques for the reconstruction of the three-dimensional back surface in order to detect a lateral scoliosis; these techniques can be adapted to sleep applications. The camera and raster slide are optimally chosen: the image processing reconstructs the back’s surface with a root mean square deviation of 0.5 mm. A raster with more raster lines or a camera with a higher resolution, therefore, is not necessary.

As a result of the image processing, the back’s surface is described by a cloud of points that are randomly distributed on the surface. Using one-dimensional linear interpolation, the randomly distributed data points are transformed to a regular grid (Frobin and Hierholzer 1985), which will simplify further calculations. Based on surface properties the line through

FIGURE 3.11 Reconstruction of line through processi spinosi. (From Drerup and Hierholzer, Clin. Biomech., 1994, 9, 28–36. With permission.)

the processi spinosi (see Figure 3.11) and anatomical landmarks—sacrum point, vertebra prominens—can be calculated accurately. The landmark localization is independent of a patient’s position and insensitive to moderate asymmetry and posture changes of the patient. The landmarks are, therefore, well suited for the objective definition of a body-fixed coordinate system.

Further, the three-dimensional line through the vertebral bodies is constructed out of (1) the line through the processi spinosi and (2) the positions of the anatomical landmarks, based on an empirical formula assuming that the vertebral rotation is equal to the surface rotation in a transversal section, as illustrated in Figure 3.12.

In comparison to radiographic scans, the positions of the geometrical centers of the vertebrae in a frontal projection can be reconstructed with a root mean square deviation of 4.6 mm \((n=478)\). The main causes for this error are the noise of the video images and the algorithmic estimation of the line through the processi spinosi and of the vertebral rotation \((±3°)\). Nevertheless the error is acceptable for the intended application. The main advantage of the system, compared to other optical techniques, is the automatic high-speed image analysis. The complete measurement system is commercialized as Formetric®.

3.1.2.9.2 Evaluation

White-light raster line triangulation visualizes the back’s surface accurately \((±0.5 \text{ mm})\) and repeatably, without detrimental effects, and without making contact with the human body. The evaluation is independent of the position of the subject with respect to the equipment, but a supine position cannot be measured. Both measurement time and analyzing time are short, since automatic and digitized image analysis and processing are applied. Limited experience is required, when anatomical landmark positions must be corrected. Only surface information is generated, but an algorithm for the extraction of the position and orientation of the vertebrae is available and has an acceptable accuracy. The cost for fully automatic and high-speed equipment adapted to sleep positions is about $50,000.
3.1.2.10 Optoelectronic Scanning

3.1.2.10.1 Description

Surfaces can be measured by different techniques of optoelectronic scanning (e.g., by projecting a laser beam on the body surface and detecting the reflected beam by a photosensitive camera). The aim is to determine the shape of a surface by measuring the three-dimensional coordinates of a set of points that samples the surface. In order to scan the entire surface of a body, the beam—or an array of beams—has to turn around the object over 360°, resulting in separate body contours. A detailed methodological description of the measurement technique can be found in literature (Besl and McKay 1992).

One example is the Optronic Torsograph (Anima Corp., Japan) that was tested by Dawson (Dawson et al. 1993). It consists of an array of 10 LEDs that are vertically mounted at a distance of 30 mm from each other, turning around a vertical axis within 5 seconds and generating 10 horizontal contours of 100 data points each. A high correlation ($r=0.8$) was calculated between the Cobb angle measured by optical and radiographic scanning techniques. Optical scanning can be used for scoliosis evaluation.

Another example is the Fast SCAN handheld laser scanner by Polhemus (see Figure 3.13). This optoelectronic scanner digitizes an object, while appropriate software is able to create complex three-dimensional models out of the generated point cloud. The accuracy is relatively high (±1 mm), and the scanning process is relatively fast compared to most other techniques—except white-light raster line triangulation—so this technique might be applied to scan a subject.

Optoelectronic scanners generate only surface information. Consequently, a mathematical analysis is needed to extract the vertebral column out of the surface generated by the equipment. This requires high-resolution equipment (to create a dense point cloud for an accurate surface analysis) at a high speed (to cope with human motion).
3.1.2.10.2 Evaluation

Optoelectronic scanners are able to visualize the back’s surface in an accurate (±1 mm) and repeatable way, without detrimental effects, and without making contact with the human body. The evaluation is independent of the position of the subject with respect to the equipment, but a supine position cannot be measured. Both measurement time and analyzing time are short when automatic processing is applied. No experience is required, but an extra algorithm is needed to evaluate the vertebral column, since no direct information about the position and the rotation of the vertebrae is produced. The cost for fully automatic and high-speed equipment is relatively high (about $50,000).

3.1.2.11 Holography

3.1.2.11.1 Description

A picture carries information on the light amplitude reflected by an object. In order to get a three-dimensional impression (e.g., to produce a hologram), both the amplitude and the phase of the original light wave have to be reconstructed. This can be realized, as illustrated in Figure 3.14, by splitting the source wave into a reference part that is projected on a photographic plate by a lens, and into a second part that falls on the object to be reflected on the same plate. The two bundles of incident light have to be coherent—as is the case for laser light—but they have a different phase that will cause them to interfere on the plate. The grid of the interference lines, called the “hologram,” depends on the nature of the object.

![FIGURE 3.14 Hologram construction.](image1)

![FIGURE 3.15 Hologram reconstruction.](image2)
The interference grid is not perceptible with the naked eye and has to be reconstructed by projecting the reference wave on the developed hologram, as illustrated in Figure 3.15. The hologram wave fronts carry the same information as those originally reflected by the object. Different images are observed when looking at the hologram under different angles. A part of the top, the bottom, and the sides will be visible, giving a three-dimensional impression. A detailed description of this optic technique can be found in the literature (Miler et al. 1978).

To scan a relatively large surface (e.g., a back’s surface) a strong laser (e.g., Argon) has to be used, and the diaphragm, which is only a few µm wide, has to be resistant to this power. A relatively short closing time (e.g., 0.02 seconds) will avoid the blurred images caused by possible posture changes of the subject. The resulting image can be quantified during the reconstruction phase by moving a LED behind the hologram until it takes the same position as a sharp point of the virtual image of the surface, and by measuring distances between several points manually. Consequently, this surface reconstruction is limited by the accuracy of the human eye—not able to distinguish spinous processes on a hologram—and only surface information is generated.

### 3.1.2.11.2 Evaluation

Optic holography is able to visualize a back’s surface by generating a three-dimensional point cloud. It has no detrimental effects, and no contact with the human body is made. The evaluation is independent of the position or the orientation of the subject with respect to the equipment, but a three-dimensional image can be observed only within a limited angle. Measurement time is short, but no automatic processing is available currently. Consequently, operator intervention limits practicality, since a considerable amount of manual interaction is required to quantify surface properties. Other limiting factors include restricted accuracy and repeatability, the number of postures that can be measured, and the fact that an extra algorithm is needed to evaluate the vertebral column, since only surface information is produced. The cost is about $50,000.

### 3.1.3 Comparative Evaluation of Different Measurement Techniques

A two-dimensional matrix enables an objective comparison of the different measurement techniques for the properties that were discussed earlier. A

<table>
<thead>
<tr>
<th>Performance</th>
<th>User-friendliness</th>
<th>Applicability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Complete</td>
<td>Accurate</td>
<td>Repeatable</td>
</tr>
<tr>
<td>WEIGHT</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>X-rays</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Ultrasound</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>MRI</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
weight factor has been assigned to each of these properties. Characteristics that typify the performance of the system (e.g., accuracy) are relatively more important than those parameters typifying the user-friendliness of the system (e.g., measuring time). Aspects that put a direct limit on the applicability (e.g., detrimental effects) are most important.

Plus signs in the matrix in Figure 3.16 have the following connotation:

Performance (weight=2):

- Complete depiction of the spine: the shape and the axial rotation of the vertebral column can be derived from the images.
- Accurate depiction of the spine: the line through the processi spinosi can be located with an accuracy of 5 mm.
- Repeatable depiction of the spine: two consequent position measurements do not differ more than 5 mm.
- Posture-independent depiction of the spine: the result is not dependent on the position of the subject with respect to the equipment.
- Correct depiction of the internal spine: the vertebral positions can be located or calculated with the same accuracy.
- Limited body contact: no contact with the subject is made that would influence the accuracy.

User-friendliness (weight=1):

- Limited measuring time.
- Limited analysis time.
- Flexibility: the technique can be used for all postures (including supine position).
- Limited rebuilding: minor investment to adjust the equipment to sleep analysis.

Direct limit on applicability (weight=4):
• Limited operator intervention/experience needed.
• Limited cost: lower than $50,000.
• No detrimental effects on human health.

Measurement techniques with detrimental effects—X-rays, CT scans—are to be excluded for ethical reasons since several tests are required to optimize a sleep system for one single person. The same decision applies for equipment rising above the intended budget, like MRI scanning and three-dimensional ultrasound scanning techniques. A third stringent factor is the level of experience needed to analyze the images, excluding holography, thermography, EMG, and ultrasound.

The remaining techniques can be subdivided into two categories, depending on whether contact is made with the subject or not. Three-dimensional tracking and geometrical instruments make contact since they require palpation, and time and (limited) experience also are necessary. The result is a line through the spinous processes, but no information on the axial rotation of the vertebrae is produced. Moiré topography, white-light raster line triangulation, and optoelectronic scanning measure the back’s surface without making contact with the subject, but algorithms are needed to extract the lines through the spinous processes and the vertebral bodies out of the surface information. The applicability of these techniques, therefore strongly depends on the availability and quality of these algorithms. A limitation of all remaining techniques is that the back’s surface has to be visible; measuring supine postures in a direct way is, therefore, excluded.

In 1994, at the start of the study that is currently under discussion, no analyzing software was commercially available for any of these second category techniques; a selection had to be made out of different geometrical and tracking instruments. Optical tracking was preferred, based on (1) the limited reliability and possible posture interference of geometrical techniques and (2) the availability of optical tracking equipment (for gait analysis). Section 3.2.1 discusses in detail how, at the first stage, a simplified two-dimensional version of this technique can be successfully applied to sleep research.

In parallel, dedicated software has been developed in order to involve three-dimensional back surface measurements without making contact. At the time of this writing, algorithms exist for the automatic and digitized quantification and analysis of surfaces measured by WLRT and optoelectronic scanning, but not for Moiré topography. WLRT is preferred, because of (1) the large optoelectronic scanning investment needed to reach the same speed and accuracy as WLRT and (2) the availability of algorithms to extract the spine out of a WLRT back surface. Section 3.2.2 discusses how at the second stage white-light raster line triangulation is applied to posture analysis.

3.1.4 Conclusion

This section analyzed and compared different measurement techniques that are able to define the shape of the human spine when lying on a sleep system. The first subsection described the properties that the ideal equipment should have. The second subsection depicted and analyzed different measurement techniques that meet these requirements to
some extent, and the third and last subsection evaluated each of the techniques individually and comparatively.

Based on this assessment it was possible to decide which equipment is most suitable for two- and three-dimensional measurements, respectively: optical tracking will be used for two-dimensional measurements of the vertebral column at the first stage; at the second stage white-light raster line triangulation will be applied to three-dimensional measurements.

3.2 Selected Measurement Techniques to Evaluate the Spine

This section describes two experimental setups that were designed, built, and used to measure the spine during bed rest in order to evaluate back-support qualities.

3.2.1 Optical Tracking

At a first stage, optical tracking was conceived for both direct and indirect measurements in order to evaluate lateral and supine positions, respectively. Both image capturing and image analysis techniques are described below.

3.2.1.1 Image Capturing

Optical tracking usually is used for human motion analysis by coupling measurement data to anatomical models, but the technique can also be used for static analyses. A camera system consisting of at least two cameras is able to measure lumbar and thoracic spinous process positions in three dimensions by tracing dedicated spherical markers that are capable of reflecting ultraviolet light. A simplified version with only one camera measures a planar projection of the spine.

For a lateral sleep position, 17 of these markers (12 thoracic and 5 lumbar) are detected by a Qualisys MAC-Reflex® camera system, as illustrated in Figure 3.17. They are glued to the skin covering the spinous processes, which are located using palpation of

![Figure 3.17 Camera measurement for lateral sleeping posture.](image)
the person in a recumbent position. A two-dimensional approximation of the vertebral curvature is obtained by projecting the markers in a frontal plane and by calculating their position with respect to two reference markers.

For supine sleep positions, a system with pins piercing through the mattress measures the spinous process positions as illustrated in Figure 3.18. A conducting strip—glued to the spinous process locations—in combination with an electrical circuit ensures permanent contact between the pins and the spinous processes. Two reference markers allow recalculating of the positions of the markers mounted on the lower side of the pins to the actual spinous process positions.

![Camera measurement for supine sleeping posture.](image)

**FIGURE 3.18** Camera measurement for supine sleeping posture.

Systematic errors are traced, quantified, surmounted by software (e.g., by lens correction), and calibration of the equipment (Notelaers and Oris 1997). Technique-specific errors on marker tracing (±0.12 mm) and pin positioning (±0.39 mm) were calculated (Notelaers and Oris 1997) and appeared to be small in comparison to the uncertainty introduced by the poor relationship between skin marker position and spinous process position due to palpation errors (±4 mm). Including calculation (±0.05 mm) and interpolating errors (±2 mm) results in a substantial total error (±5 mm) on the XY coordinates of the spinous processes.

Measurements are performed five times on every person in order to enhance the estimation of the measured spinal deformations. Before each exposure the person remains recumbent for 15 minutes to allow the muscles to relax. The subject has to be positioned in the same way for all analyzed sleep systems and for all exposures in order to achieve a correct comparison. Posture, therefore, is controlled by adopting (1) an erect posture in case of a supine sleep position and (2) the semi-Fowler’s position in case of a lateral position. This absolute positioning is controlled by anatomical landmarks: the spina iliaca anterior superior, the acromion, and the top of the head are located by palpation and positioned at a fixed distance in the cranio-caudal direction from the mattress end. After each measurement the person being tested takes a short pause and is correctly repositioned by relocating the anatomical landmarks.
3.2.1.2 Image Analysis

The spinous process positions are automatically digitized and transferred into a spreadsheet format for further analysis. The position and orientation of the vertebrae are estimated, and the shape of the spine is evaluated based on different parameters depending on the posture.

In the case of a supine position, the spinal column has to approximate the natural thoracic kyphosis and lumbar lordosis (see Section 1.1.1.1. for the anatomy of the spine), yet slightly smoothened by the fact that, in a sleep position, the direction of the gravitation vector no longer coincides with the cranio-caudal direction of the body: a prolongation of the spine of 2% and a consequent smoothening is applied to the reference.

Subsequently, the deviation from this reference shape is quantified by a weighted average of five parameters (P₁ to P₅). The first four are estimations of the preservation of the thoracic kyphosis and the lumbar lordosis, as compared to the reference. The mean absolute distance P₃ from the spinal curvature to its least square line (illustrated in Figure 3.19, with L₅ the most distal lumbar vertebra and T₁ the most proximal thoracic vertebra) gives an overall evaluation. A detailed mathematical description of result processing is included in Chapter 5.

For a lateral position, the frontal projection of the line through the spinous processes is compared to a straight line; the deviation from this reference shape is quantified by three parameters (P₆ to P₈), which will be discussed in detail in Chapter 5. The mean distance of the Y coordinates of the spinous processes to the least square line through the measured points is the first parameter P₆ (by analogy with parameter P₅ in Figure 3.19). The angle of the same least square line in the reference coordinate system is the second parameter P₇. Further, the spinal slope usually shows a discontinuity around the vertebra T₁₁, and measurement points can, therefore, be subdivided into two parts separated by this vertebra. For each part, the least square line is calculated; the angle between the two lines is the third parameter P₈. A detailed mathematical description of measurement result processing—and methodology in general—is discussed in Chapter 5.

![FIGURE 3.19 Sagittal shape of the spine: parameter P5.](image)
3.2.2 White-Light Raster Line Triangulation

People do not limit themselves to two-dimensional sleep positions, making the expansion to three-dimensional measurements a logical second step. White-light raster line triangulation hardware and active contour software were successfully applied to the evaluation of the spine in three-dimensions, as described by Huysmans et al. (2000). Raster stereography is a technique to quantify three-dimensional surfaces based on the fact that a regular light pattern will deform on an irregular surface; the technique is derived from stereo photography, using triangulation to calculate three-dimensional values from the grid projection.

Hierholzer et al. created the foundation of the WLRT image-capturing technique; this paragraph will therefore not focus on the image-capturing hardware, but concentrate on the image analysis software.

3.2.2.1 Image Capturing

White-light raster line triangulation (WLRT) enables the scanning of three-dimensional objects by projecting raster lines on its surface and by capturing these lines under a known and fixed angle with a camera, as illustrated in

FIGURE 3.20 WLRT image capturing by a grid projector (right) and a camera (left).
Flexible construction holding a grid projector and a camera.

Figure 3.20. The projector and the camera are mounted into a flexible construction to enable multipurpose measurements of the spine (see Figure 3.21). This construction enables the assessment of all postures between a lateral and a prone sleep position.

In order to enable automated processing, the projected raster consists of a pattern of thick and thin lines, being a projection of slide lines with a thickness of 60 and 40 µm, respectively. The camera has a resolution of 739 by 574 pixels—739 in longitudinal direction—and the working distance of the system is 2 m. Further, a stereo base of 0.8 m and a convergence angle of 22° are used, resulting in a line raster density of one line per 7.5 mm on the back’s surface (see Figure 3.22). The spatial resolution of the camera at the site of the object is 1 pixel per square millimeter.

The camera is connected to an 8-bit video digitizer storing each frame in the PC video memory, which is directly accessible by the microprocessor. A
so-called “frame grabber” projects the digitized image on the screen, and software traces and reconstructs the raster lines by light-intensity peak detection and line sequence analysis, respectively. Based on triangulation algorithms, spatial coordinates of all raster points are calculated, resulting in a dense point cloud of randomly distributed points, indicating the raster lines and describing the measured surface. Using one-dimensional linear interpolation the randomly distributed data points are transformed to a regular grid, which will simplify further calculations and the mathematical reconstruction of the surface, as illustrated in Figure 3.23.

By 1981, Frobin and Hierholzer had developed appropriate hardware for the assessment of a back’s surface in order to detect a lateral scoliosis (Frobin and Hierholzer 1981). Both the camera and the raster slide were optimally designed for measuring a back’s surface—an overall root mean square deviation of 0.5 mm is obtained on the coordinate positions of the points sampling the back surface—and can easily be calibrated (Hierholzer 1994) and adapted to sleep applications. Increasing the number of raster lines or the camera resolution, therefore, is not necessary.

In the framework of the present study, both the repeatability and the sensitivity of the measurement technique are evaluated for sleep applications. At first, measurement repeatability is tested on a plaster cast model of the back’s surface, in order to eliminate errors due to position shifts. The introduced standard deviation on sagittal positions (Z coordinate in Figure 3.23) proves to be very small (0.03 mm), while the standard deviation on lateral and longitudinal positions (X coordinate and Y coordinate, respectively) is acceptable (0.15 mm).

Further, the sensitivity of the equipment to several external parameters is tested:

- When rotating the measurement equipment around a longitudinal axis with respect to the person, this rotation should not exceed 45°; otherwise, the standard deviation on all coordinate positions will significantly increase.
- When a part of the back’s surface is invisible, reconstruction of the back’s surface will occur with the same accuracy and repeatability. Bad visibility or the inability to trace
one of the anatomical landmarks, however, may lead to a standard deviation of 1 cm on the estimated coordinate positions of the vertebral midline.

- When axillary points (i.e., the arm pit points) are entered through a user interface, the influence on the results is negligible compared to the overall accuracy of the system.
- When manually correcting the anatomical landmarks, the introduced standard deviation on lateral and longitudinal positions of the vertebral midline (X coordinate and Y coordinate, respectively) does not exceed 2 mm, while the standard deviation on sagittal positions of the vertebral midline (Z coordinate) does not exceed 1 mm.

The influence of mathematical errors (e.g., rounding off a Taylor series approximation after the second-order terms (Frobin and Hierholzer 1982)) is negligible compared to the overall accuracy of the system.

### 3.2.2.2 Image Processing

The next paragraph describes active contour models and how they are used to analyze so-called “invariant shape properties” of the back’s surface (i.e., properties that are independent from the position of the surface with respect to the measurement equipment). Drerup and Hierholzer (1985) analyzed the shape of the vertebral column based on surface properties; both anatomical landmarks (Drerup and Hierholzer 1994; Frobin and Hierholzer 1981) and the line through the spinous processes (Drerup and Hierholzer 1987) are traced as starting points for the reconstruction of the inner spine. The strength of the relationship between external and internal anatomical spine parameters is, however, unclear. Divergent theses are posed in literature, including authors arguing a poor relationship (Refshauge et al. 1994). Caution, therefore, is required before jumping to conclusions about the position and orientation of the vertebrae. Consequently, a detailed error analysis for both image capturing and image analysis is imperative and can be checked out in the literature.

#### 3.2.2.2.1 Active Contours

The technique of active contours was first proposed by Kass et al. (1988). A certain (mathematical) “cost” is assigned to a contour so that the cost is minimized when the contour is positioned on a location with specific target properties. The objective is to move the contour on the image until the cost is minimized and appropriate contour properties are achieved. The progress of this contour resembles the crawling behavior of a snake, hence the name “snake” (Kass et al. 1988). The starting position is chosen automatically or by operator interaction, and a straight line or a spline connects the snake points.

For simple examples, only one cost term is involved. In the case of automatic detection of the edges of a photograph, a low cost is assigned to locations with a high light-intensity gradient. In the case of the automatic detection of a dark strip on an image, a low cost is assigned to dark image spots, as illustrated in Figure 3.24.
The total snake cost to be minimized is a combination of the “external” cost (e.g., the sum of the light intensity cost of all contour points) and (if so desired) the “internal” cost, governing the behavior of the curve as a whole (e.g., to obtain a circle). The external cost governs the influence of the image on the contour, while the internal cost modifies the shape of the curve itself in the absence of influence from the image environment. The benefit of an internal cost is the avoidance of solutions that are physically impossible; a “stiffness cost,” for example, achieves a smooth snake path. The total cost \( C \) of an active contour with a parametric representation \((x(s), y(s))\) can be written as:

\[
C_{\text{total}} = \int_{0}^{1} C(s) ds = \int_{0}^{1} C_{\text{internal}}(s) + C_{\text{external}}(s) ds
\]  

(3.1)

Usually a snake consists of a discrete number of points \( i \) (e.g., the spinous processes), resulting in the total cost \( C \) being a sum of partial costs \( c \) (with \( n \) the number of snake points):

\[
C_{\text{total}} = \sum_{i=1}^{n} c(i)
\]  

(3.2)

For most applications—including the tracing of the spinous process line—both the internal and the external costs consist of several terms in order to consider different
properties. Each property has a corresponding cost term, and a weighted sum of all cost terms is made based on the relative importance of each property.

3.2.2.2 Dynamic Programming

Defining the line through the spinous processes can be reduced to an active contour optimization procedure. An iterative algorithm moves the snake closer to the aimed position and to a corresponding minimal cost. Four step-by-step methods have been proposed to solve this optimization problem.

Kass et al. (1988) suggested an algorithm based on variational calculus, and Fua Brechbuhler (1996) developed a variant on this method: the steepest descent algorithm. They both describe the curve as a polygon that connects explicit points, while the vertices at these points are used as curve parameters. These methods use gradients and therefore require derivatives of the cost function to implement the minimization process. The steepest descent algorithm performs a local optimization for a specific point while keeping the other points at the previous iteration position. The variational calculus method calculates new positions of the entire curve to achieve a global optimization.

**TABLE 3.1 Optimization Method Classification**

<table>
<thead>
<tr>
<th></th>
<th>Local Optimization</th>
<th>Global Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient methods</td>
<td>Steepest descent</td>
<td>Variational calculus</td>
</tr>
<tr>
<td>Neighborhood search</td>
<td>Greedy</td>
<td>Dynamic programming</td>
</tr>
</tbody>
</table>

The other two approaches take advantage of the inherent discrete nature of the optimization problem: on a discrete image grid a finite neighborhood of a given contour is scanned to trace the optimal following position in the iteration process. The greedy algorithm—as proposed by Williams and Shah (1992)—performs a local search to find the optimal position for each individual point of the curve. In the case of dynamic programming—as described by Amini et al. (1990)—the global curve is moved in every iteration to the position that yields the largest decrease of the total cost of the curve. The different optimization methods can be classified as illustrated in Table 3.1.

Local optimization might suffer from convergence problems because the interaction of adjacent points is not taken into account. Moreover, a local optimization iteration step does not necessarily realize the largest cost decrease for the entire curve. A global minimization process requires fewer iteration steps to come to a final solution, but the computational cost for each individual iteration step is substantially higher. When comparing the steepest descent to the variational calculus method, the high number of points used to describe the curve (n) causes the latter method to be slower. When comparing the greedy method to dynamic programming, the number of points in the search neighborhood (m) is the determining factor.

In conclusion, the variational method and the method of steepest descent are both very fast, but might have convergence problems. The greedy algorithm is slower to some extent but with a much better convergence. Dynamic programming requires a long computation time, but the even better convergence properties and the global optimization, together with a good initial estimation of the curve, give priority to the latter technique.
Richard Bellman (1959) was the first to apply dynamic programming to optimization problems containing sequential decisions. Amini (1990) was the first to apply this technique to active contours.

Dynamic programming chooses the optimal contour out of all possible contours, but an exhaustive scanning of all possibilities is practically impossible: if $p$ is the area of the search neighborhood around each point and $n$ the number of snake points, there will be $p^n$ possible snakes for each iteration step. Dynamic programming, therefore, performs an intelligent and structural scan of a some of these possibilities, resulting in an efficient but not guaranteed correct solution. When a contour is composed of $n$ snake points ($v_1, v_2, \ldots, v_n$), each point can move freely within its neighborhood, which usually consists of the eight surrounding points on the image grid. The total contour cost is the sum of the costs of all individual snake points, including both external costs (e.g., image properties) and internal costs (e.g., relative position of snake points).

$$C(v_1, v_2, \ldots, v_n) = \sum_{i=1}^{n-1} c(i) = C_{\text{total}}$$

Dynamic programming usually simplifies the internal cost by limiting the interdependence of the points to maximally two other snake points, resulting in the following total cost:

$$C_{\text{total}} = C(v_1, v_2, \ldots, v_n)$$

$$= c_1(v_1, v_2, v_3) + c_2(v_2, v_3, v_4) + \cdots + c_{n-2}(v_{n-2}, v_{n-1}, v_n)$$

$$= \sum_{i=1}^{n-2} c_i(v_i, v_{i+1}, v_{i+2})$$

Dynamic programming then minimizes the total cost by a layered decision process: the algorithm combines the first cost portion (defined by the first three points) with the second cost portion (points 2, 3, and 4) until a minimal cost is achieved and repeats this method until the end of the contour is reached. In order to minimize the first cost portion, the algorithm decides for each possible combination of snake points 2 and 3 which point in the neighborhood of snake point 1 is optimal. For the following combinations of snake points the same method is used to minimize the consecutive cost portions. As a result, subfunctions $\{s_i\}_{i=1}^{n-2}$ are generated solving one-dimensional minimization problems. All costs are saved and combined in order to minimize the total cost and to define the corresponding optimal snake, as illustrated below ($n=5$). The difference with an exhaustive global algorithm is that combinations of cost portions of curve fragments are minimized instead of the total curve cost as a whole, which does not necessarily result in the optimal global curve, as mentioned before.
Figure 3.25 illustrates this procedure for a simple example, including 4 snake points \((v_1, v_2, v_3, v_4)\) with a neighborhood of two possibilities each (a and b). For every combination of \(v_2\) and \(v_3\) the algorithm traces the optimal position of \(v_1\) to minimize the first cost portion \(C_1(v_1, v_2, v_3)\), and for every combination of \(v_3\) and \(v_4\) the algorithm gives the optimal position of \(v_2\) to minimize the second cost portion \(C_2(v_2, v_3, v_4)\), as illustrated on the figure by solid lines. These optimal combinations are also filled out in position matrices, resulting in one matrix with four combinations for each cost portion.

For the remaining combinations of \(v_4, v_3, \text{and} v_2\) in the second matrix, the best value for \(v_1\) is chosen from the first matrix. The total cost (the sum of the two cost portions involved) is calculated for every complete combination \((v_1, v_2, v_3, v_4)\), out of which the one with the lowest total cost is chosen. This results in one complete optimal combination fixing the next iteration step of the snake.

\[
s_1(v_2, v_3) = \min_{v_1} C_1(v_1, v_2, v_3)
\]
\[
s_2(v_3, v_4) = \min_{v_2} \{s_1(v_2, v_3) + C_1(v_2, v_3, v_4)\}
\]
\[
\min_{v_1, v_2, v_3, v_4} C(v_1, v_2, v_3, v_4) = \min_{v_4} \{s_2(v_3, v_4) + C_3(v_3, v_4, v_5)\}
\]
3.2.2.3 Cost Definition

In order to apply active contours and dynamic programming to the definition of the line through the spinous processes, traceable back properties and matching weights have to be defined to determine the corresponding internal and external costs. All shape properties of the back have to be independent from the position and orientation of the patient and insensitive to moderate patient asymmetry. A short introduction to all costs involved is described here; a detailed description can be found in literature.

3.2.2.3.1 Curvature—The first important surface entity is the curvature, which is dependent on local image properties, and therefore acts as an external cost. The back’s surface has a high concavity at the position of the vertebral column, especially in the lumbar and sacral regions. Using only curvature costs will, however, result in incorrect snake behavior, as illustrated in Figure 3.26. Other properties—including symmetry—will be included.

Since a surface is a two-dimensional entity, at least two parameters are needed for a complete description of the local curvature. Starting from a second-order approximation in the neighborhood of a point, the curvature in a certain direction can be calculated as the inverse of the radius of the tangent circle: \( \kappa = 1/\rho \). In each point, two perpendicular directions can be found where curvatures are extreme: the principal curvatures \( \kappa_1 \) and \( \kappa_2 \). Based on these principal curvatures two other curvatures can be defined, namely, the Gaussian curvature \( K = \kappa_1 \cdot \kappa_2 \) and the mean curvature \( H = \frac{1}{2} (\kappa_1 + \kappa_2) \). The sign of the Gaussian curvature enables elliptic areas to be distinguished from hyperbolic (saddle-shaped) areas, as illustrated in Figure 3.27. Similarly, in the case of parabolic and elliptic areas, the sign of the mean curvature

**FIGURE 3.26 Incorrect snake behavior.**

curvature costs will, however, result in incorrect snake behavior, as illustrated in Figure 3.26. Other properties—including symmetry—will be included.
allows a distinction between convexity and concavity. Based on these curvatures the back’s surface can be divided in convex, concave, and saddle-shaped zones.

3.2.2.2.3.2 Symmetry—For normal, healthy people (e.g., no scoliosis) the medial sagittal plane is a symmetry plane enclosing the vertebral column. This symmetry is manifested at the surface level, even during sleeping. Symmetry, therefore, can be used to trace the position of the spine by locating zones of minimal asymmetry (Hierholzer 1985), especially in the lumbar and thoracic region, thanks to the high curvature and the convexity at the scapulae, respectively. Symmetry is dependent on local image properties and acts as a second external cost.

In each point $P$ of the surface, the asymmetry function (Drerup and Hierholzer 1996) is defined by making a transversal cross section and by comparing the curvatures at points left and right of $P$. Based on the principal curvatures $\kappa_1$ and $\kappa_2$ (see Section 3.2.2.2.3.1), the curvature in an arbitrary direction $\alpha$ can be calculated, with $\alpha$ the angle between the considered direction and the principal direction corresponding with the curvature $\kappa_1$.

$$\hfill \kappa(\alpha) = \kappa_1 \cos^2 \alpha + \kappa_2 \sin^2 \alpha$$

At the same distance from $P$, two points $P_{\text{left}}$ and $P_{\text{right}}$ are defined at the left and at the right side of $P$; $\varphi_{\text{left}}$ and $\varphi_{\text{right}}$ are the angles between the respective principal directions at these points and a transversal axis. Each curvature at $P_{\text{left}}$ making an angle $\alpha$ with the transversal axis has a mirror point $P_{\text{right}}$ making an angle $\pi - \alpha$ with the same axis. Curvatures left and right with corresponding directions are equal in the case of perfect symmetry and are calculated as follows:

$$\hfill \kappa_{\text{left}}(\alpha) = \kappa_1 \cos^2 (\alpha - \varphi_{\text{left}}) + \kappa_2 \sin^2 (\alpha - \varphi_{\text{left}})$$

$$\hfill \kappa_{\text{right}}(\alpha) = \kappa_1 \cos^2 (\pi - \alpha - \varphi_{\text{right}}) + \kappa_2 \sin^2 (\pi - \alpha - \varphi_{\text{right}})$$

FIGURE 3.27 Curvature classes.
Further, the amount of asymmetry between $P_{left}$ and $P_{right}$ can be calculated as the integral (from 0 to $\pi$) of the square of the difference between the corresponding curvatures:

$$a = \frac{1}{\pi} \int_0^\pi \left( \kappa_{left}(\alpha) - \kappa_{right}(\alpha) \right)^2 d\alpha$$

(3.8)

This integral represents the contribution of one pair of points. The total symmetry cost of $P$ is the integral of $a$ over the entire transversal cross section, with $b$ the width of the integration interval.

$$A = \frac{1}{b} \int a \, dx$$

(3.9)

Since the function $a$ will be calculated in a discrete number of surface points, the integral will be converted into a sum, with $n$ the number of points at the left side of $P$, having a mirror point with respect to $P$.

$$A = \frac{1}{n} \sum_{i=1}^n a_i \Delta x$$

(3.10)

When a subject sinks into the mattress, part of the back’s surface will become invisible, reducing the area that can be used to calculate asymmetry values; in order to apply the described procedure, at least two thirds of the back’s surface should be visible. Further, it is possible that (local) minimal asymmetry is detected at several spots of a transversal cross section, which is solved by the fact that all minima together should produce a continuous line.

3.2.2.2.3.3 Bending—The curvature and symmetry have corresponding external costs to force the snake toward the right location. The result, however, will be rather fanciful and will not resemble the somewhat stiff behavior of the spine if the total cost is influenced only by these factors. As an example, bending the thoracic portion of the vertebral column is difficult (as compared to the lumbar and cervical portions) due to the presence of the rib cage. In order to avoid results that are physically impossible (Panjabi et al. 1981), internal costs are added, including bending and torsion properties of the spine. Figure 3.28 illustrates the influence of adding a bending stiffness: based on only the external costs, the snake will be attracted by a concave zone next to the lumbar vertebral column (left), which can be corrected by adding a bending stiffness to prevent from lateral shifting (right).

Without a reference bending, the algorithm shapes the snake to the outline of the vertebral column, starting from a straight beam. Not including the absolute bending but including the bending difference with a reference value (e.g., the bending of the spine in an upright posture) can significantly improve the algorithm.
FIGURE 3.28 Corrective process of adding a bending cost.

With \( \vec{s}(i) \) the natural parameterization alongside the snake and \( \vec{s}(i) \) the three-dimensional coordinate of a snake point for \( 2 \leq i \leq n-1 \), the mathematical description of the bending vector difference is as follows:

\[
|k| = \sqrt{\left(\vec{s}(i+1) - 2\vec{s}(i) + \vec{s}(i-1) - \text{bending ref}\right)^2}
\]  

(3.11)

3.2.2.3.4 Torsion—In order to define a three-dimensional curve unambiguously, bending properties alone are not sufficient. Torsion—and the continuity of the torsion function alongside the snake—has to be included as a second internal cost to limit the relative position of the snake points. The optimization algorithm (Degraeuwe and de Blauw 2000) uses only three snake points (the point itself, the next, and the previous one) to calculate the torsion at a certain snake point \( \vec{s}(i) \) with \( 2 \leq i \leq n-1 \). The program first calculates the direction of the tangent lines to the curve in the points \( \vec{s}(i-1) \) and \( \vec{s}(i+1) \) with a forward and backward differential, respectively.

\[
\vec{t}(i-1) = \vec{s}(i) - \vec{s}(i-1) \quad \text{and} \quad \vec{t}(i+1) = \vec{s}(i+1) - \vec{s}(i)
\]  

(3.12)

The torsion \( \vec{T}(i) \) in the point \( \vec{s}(i) \) can be calculated, starting from the normal \( \vec{n}(i-1) \) and \( \vec{n}(i+1) \) and the binormal in the surrounding points \( \vec{s}(i-1) \) and \( \vec{s}(i+1) \).

\[
\vec{b}(i-1) = \vec{t}(i-1) \times \vec{n}(i-1) \quad \text{and} \quad \vec{b}(i+1) = \vec{t}(i+1) \times \vec{n}(i+1)
\]  

(3.13)

\[
\vec{T}(i) = \frac{\vec{b}(i+1) - \vec{b}(i-1)}{2}
\]  

(3.14)

The torsion cost will prevent the snake from shifting aside, especially in the cervical region where no significant concavity can be located in the neighborhood of the vertebral column (Ordway et al. 1997). Figure 3.29 illustrates a lateral shift to a zone with a high curvature, also influencing the thoracic behavior of the snake; on the right, Figure 3.29 pictures the corrective process of a torsion cost.
3.2.2.3.5 Equidistance—During the calculations, snake points will mount up at places with a high curvature or symmetry, so that bending and torsion will be minimized at these places. To avoid this effect, a final internal cost is included to keep all snake points at an equal distance. Further, equidistance also simplifies the derivative formulas that are used to calculate the bending and torsion costs. The total length of the spine $l_{\text{spine}}$ and the number of snake points determine the equidistant length of each segment. The deviation from this length is the equidistance cost, but differences of the order of magnitude of the grid are not penalized.

\[
\text{Equidist}(i) = \left( \frac{\hat{s}(i) - \hat{s}(i-1) - l_{\text{equi}}}{\Delta y} \right)^2 \quad \text{with} \quad l_{\text{equi}} = \frac{l_{\text{spine}}}{n-1}
\]  

(3.15)

3.2.2.4 Weight Definition

Each internal and external cost does not work in the same way or at the same level. The equidistance cost works alongside the entire snake, but other costs are useful only in certain regions. Further, the relative importance of the costs can differ depending on the location on the back’s surface; all snake points have to shift to positions with a unique combination of surface properties. The following explains how the total cost is subdivided in each snake point, in order to obtain an optimal approximation of the line through the spinous processes.

The software program will first subdivide the snake into three different parts—cervical, thoracic, and lumbar—with different weighting costs. The high torsion cost needed in the cervical part (to avoid lateral shifting) justifies a separate cervical part including the upper two snake points. Further, the thoracic and lumbar parts are separated at the bending point, which is situated at roughly one third of the total height of the back. Finally, the sacrum gets the same cost distribution as the lumbar, except for the curvature cost, which is higher to ensure a fixed sacral position. The algorithm evaluates this subdivision after each iteration step.

In order to define the weighting costs for each region, the costs were first scaled (to obtain a similar order of magnitude) and further multiplied by a weighting factor from 0 to 10. External costs—curvature and symmetry—were considered first, because they are responsible for moving the snake toward the right position. In the sacral region the...
curvature reaches a local maximum, which is traced by including a relatively high curvature cost. In the lumbar region the curvature is the most important factor, while the thoracic region is characterized by high symmetry. As mentioned before, the

**TABLE 3.2 Regional Cost Contribution for Upright and Lying Positions**

<table>
<thead>
<tr>
<th></th>
<th>Upright</th>
<th>Lying</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Curvature</td>
<td>Symmetry</td>
</tr>
<tr>
<td>Cervical</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Thoracic</td>
<td>10%</td>
<td>40%</td>
</tr>
<tr>
<td>Lumbar</td>
<td>30%</td>
<td>30%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Curvature</th>
<th>Symmetry</th>
<th>Bending</th>
<th>Torsion</th>
<th>Equidistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cervical</td>
<td>5%</td>
<td>0%</td>
<td>55%</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>Thoracic</td>
<td>10%</td>
<td>30%</td>
<td>20%</td>
<td>30%</td>
<td>10%</td>
</tr>
<tr>
<td>Lumbar</td>
<td>30%</td>
<td>10%</td>
<td>20%</td>
<td>30%</td>
<td>10%</td>
</tr>
</tbody>
</table>

**FIGURE 3.30** Correct tracing of line through spinous processes.

cervical spine cannot be traced by external costs only; internal costs—bending, torsion and equidistance—are therefore added. As shown in Table 3.2, the cervical spine needs high internal cost weights; the lumbar spine is rather supple, resulting in low internal cost weights; and the thoracic is relatively stiff. In the case of an upright standing posture there is almost no spine torsion, resulting in different weighting.

An optimal cost distribution is able to trace the line through the spinous processes in a correct way, as illustrated in Figure 3.30. A complete validation of both cost and weight definitions is described in the literature.

### 3.2.2.2.5 Software Implementation

All mathematical procedures are implemented in MATLAB® software (Degrauwew et al. 2000; DeWilde and Porteman 1999). Measurements can be read, analyzed, and adapted manually through an automated graphical interface. Figure 3.31 illustrates how snake behavior can be monitored on the screen.
3.2.2.2.6 Dynamical Measurements

The same measurement technique can also be used for dynamical measurements of the spine. Figure 3.32 illustrates three consequent frames (at a frame rate of 10 images per second) during a flexion-extension movement of the spine. This measurement technique is patented and commercialized by Diers International GmbH, Germany.

![Software implementation of the snake algorithms.](image1)

**FIGURE 3.31** Software implementation of the snake algorithms.

![Dynamical measurements.](image2)

**FIGURE 3.32** Dynamical measurements.

3.3 Conclusion

As a result of comparing different measurement techniques, WLRT hardware is used to locate the spinous process positions of a person while lying on a sleep system. The main advantages of this system are that the person is not subjected to harmful radiation, the system has short measurement and computation times, and no contact with the measured surface is required. Active contour models and dynamic programming are successfully
applied to the tracing of the three-dimensional curve through the spinous processes of a person in an upright and a sleep position. Chapter 5 will discuss the actual measurements and how they are implemented.

References


Drerup, B. and Hierholzer, E., Objective determination of anatomical landmarks on the body surface—measurement of the vertebra prominens from surface curvature, J. Biomech., 1985, 18(6), 467–474.


As explained in the first two chapters, the most important environmental component affecting the mental and physical quality of sleep is the sleep system (i.e., mattress+support structure+pillow) on which we are “lying and relying.” Due to an insufficiently adapted sleep system, the human body—especially the vertebral column—is often supported unsatisfactorily, resulting in low back pain or sleep disorders in general.

The third chapter described which measurement techniques are able to evaluate the shape of the spine during bedrest, and how these techniques can be applied to gain insight into the influence of different parameters (e.g., anthropometrical characteristics) on the position of the vertebral column on a sleep system. The main problem of this modus operandi is that elaborate measurements are needed to establish an accurate correlation between anthropometrical properties and optimal sleep system characteristics for all population groups. Further, it is often difficult to find an adequate group of test persons (e.g., people with extreme body dimensions) or sleep systems (e.g., at an experimental stage); also (expensive) expert time is needed throughout all the stages of the measurement process.

This chapter will therefore describe the possibilities to overcome these elaborate procedures by simulating measurements.

4.1 Which Simulation Techniques Are Able to Evaluate the Spine?

This section describes four different simulation techniques: graphic modeling, linear numerical modeling, finite element modeling, and neural networking.

The main advantage of simulations is the fact that the number of measurements needed considerably decreases. Nevertheless, a limited number of measurements is always necessary for model validation. Furthermore, new concepts of sleep system design can be evaluated without actually building prototypes, and people with extreme body dimensions can be assessed without actually measuring them.

As sleep system research labs clearly express the demand for visualizing a parameterized model in order to integrate individualized information into a design, the first subsection illustrates the graphic modeling of both subject and sleep system with Working Model® software, which is particularly suited to model multibody dynamics in a graphic way. Due to limited CPU power, however, an accurate real-time simulation and a clear visual representation seem to be incompatible at present, so faster linear numerical models—without real-time visualizations—have been developed based on multibody dynamics, as described in the second subsection. These models allow calculating both the sleep system that offers an optimal spinal alignment and the best system out of a limited
range. A similar outcome can be realized in a more accurate way by finite element modeling, as deformations of parts of the human body can be modeled, but also more input parameters are required, as described in the third subsection.

The fourth and last subsection illustrates the possibility to use neural networks for the simulation and evaluation of measurements (e.g., those described in Chapter 5). These networks aim to predict how a certain person $x$ will be supported by a sleep system $y$ and to establish a nonlinear correlation between anthropometrical properties and optimal sleep system characteristics.

4.1.1 Graphic Modeling

4.1.1.1 Technique

The aim is to visualize not only how a sleep system deforms when a subject loads it, but also how a subject—especially the vertebral column—adjusts him/herself to the sleep system. So not only the final result but also the quasi-static simulation should be visualized, which is possible with Working Model® software.

As the multibody dynamics model will be used in a retail environment, limited calculation time is the most important restriction. The model must therefore be designed as simple as possible, the only requirement, being that it should be able to demonstrate the support qualities of a certain sleep system for a particular subject, with a significant difference toward other systems.

First, a straightforward subject model is described, which is parameterized based on simple, easy-to-measure body dimensions. Second, a mattress model is built using springs and combined with the subject model to obtain a three-dimensional evaluation.

4.1.1.2 Subject Modeling

4.1.1.2.1 Two-Dimensional Modeling

Excluding the influence of the arms and joining both legs into one simulation object—simplifications that will not do too much harm to the accuracy of
this model—a first simplified subject model consists of 11 body parts, including the head, the neck, eight trunk parts, and the legs (see Figure 4.1). Rigid rods connect the consecutive deformable blocks that represent the trunk. The mobility of each part of the trunk (e.g., the lumbar part) can be modified by adjusting the gaps between the blocks, or by changing the number of blocks used to represent it (e.g., larger number of blocks in the lumbar area).

4.1.1.2.2 Parameterization

Second, the simplified model is shaped according to a limited number of subject dimensions (see Chapter 5). Based on five basic body dimensions (shoulder width, waist width, pelvic width, body length, and body weight), a parameterized 2D subject model is generated in an AutoCAD®-environment and is exported to a Working Model® format. All procedures are automated by means of the programming language AutoLISP®. Further, a MATLAB® script is used to calculate the weight properties of the blocks, based on the same basic body dimensions. Also, elasticity characteristics and friction coefficients are added.

4.1.1.2.3 Three-Dimensional Modeling

Similar AutoLISP® and MATLAB® procedures have been developed to create a three-dimensional subject model with Working Model 4D® software, which is able to handle three-dimensional simulations. Three-dimensional modeling—and its consequent parameterization—is, however, relatively complex (e.g., concerning the degrees of freedom between the blocks), so a 2.5D model (two-dimensional with a fixed height in the third dimension) is developed at a first stage. The trunk is subdivided in 18 blocks: one for each thoracic \( n=12 \) and lumbar vertebra \( n=5 \), and one for the pelvic area, as illustrated in Figure 4.2. The main added value of a 2.5D model, when compared to a two-dimensional model, is the enhanced estimation of human body constitution, and the fact that the same 2.5D model can be used for the analysis of different two-dimensional sleeping postures (e.g., a lateral and a supine position).

FIGURE 4.2 Parameterized 2.5D subject model.
At the second stage a conceptual full three-dimensional model is developed (see Figure 4.3). This model is, however, still too rudimentary to be used in a three-dimensional simulation. It rather shows the possibilities of a three-dimensional extension. The main advantage of a three-dimensional multibody model when compared to a 2.5D model is the enhanced estimation of human body constitution (e.g., by introducing spherical shapes).

4.1.1.3 Sleep System Modeling

4.1.1.3.1 Two-Dimensional Modeling

The sleep system is represented by nine deformable blocks, each with a length of 0.2 m in the cranio-caudal direction and a height of 0.12 m, except for the first block (modeling the head cushion as well). The mobility of the blocks is limited to a vertical translation and a rotation around the center of mass, while springs and dampers connect the blocks to the ground (see Figure 4.4). As discussed in Chapter 1 (and demonstrated throughout Chapter 5), an adequate sleep system is able to deform locally (e.g., when indenting the hip zone, it should deform independently without exerting too much influence on either the shoulder zone or leg zone), which partly justifies the simplification of leaving out horizontal connections.
4.1.1.3.2 Parameterization

Sleep system characteristics can be adjusted by changing the properties of the springs and the dampers, and by adding elasticity and friction coefficients. The mass of the sleep system is only of secondary importance and, therefore, cannot be changed. All modifications take place interactively—even during the simulation—by means of a control panel that is added by Working Model® software, as illustrated in Figure 4.4.

When the optimal sleep system characteristics for a particular subject are desired, dedicated spring and damper properties can be calculated starting from the anthropometrical properties of the different body blocks (see Section 4.1.1.2), such as body block width and weight in a lateral sleep position.

When the best sleep system has to be chosen from a limited range—which will usually be the case as this tool is meant to be used in a retail environment—the most important task is to parameterize the model according to existing sleep system characteristics.

As an example, polyurethane mattresses are modeled. This mattress is subdivided into different zones, and the core stiffness (according to CTBA standards ([Möbelfacta 1990], see Chapter 5) is measured in a discrete number of points and interpolated over the entire bed surface (see Table 4.1).
FIGURE 4.5 Variation of polyurethane mattress characteristics in a longitudinal cross section.

TABLE 4.1 Polyurethane Characteristics Simulated in Two Dimensions by Spring Coefficients (N/m)

<table>
<thead>
<tr>
<th>Cranio-Caudal Distance</th>
<th>Homogeneous Stiffness</th>
<th>Firm Pelvis</th>
<th>Soft Pelvis</th>
<th>Soft Shoulder</th>
<th>Firm Waist</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.55 m</td>
<td>0.3125</td>
<td>0.3030</td>
<td>0.3125</td>
<td>0.2353</td>
<td>0.3077</td>
</tr>
<tr>
<td>0.65 m</td>
<td>0.3125</td>
<td>0.2985</td>
<td>0.3077</td>
<td>0.2500</td>
<td>0.3175</td>
</tr>
<tr>
<td>0.75 m</td>
<td>0.3125</td>
<td>0.2985</td>
<td>0.2985</td>
<td>0.2817</td>
<td>0.3333</td>
</tr>
<tr>
<td>0.85 m</td>
<td>0.3125</td>
<td>0.3077</td>
<td>0.2703</td>
<td>0.2985</td>
<td>0.3226</td>
</tr>
<tr>
<td>0.95 m</td>
<td>0.3125</td>
<td>0.3226</td>
<td>0.2326</td>
<td>0.2985</td>
<td>0.2941</td>
</tr>
<tr>
<td>1.05 m</td>
<td>0.3125</td>
<td>0.3279</td>
<td>0.2299</td>
<td>0.2985</td>
<td>0.2985</td>
</tr>
<tr>
<td>1.15 m</td>
<td>0.3125</td>
<td>0.3175</td>
<td>0.2597</td>
<td>0.2985</td>
<td>0.3448</td>
</tr>
</tbody>
</table>

Based on these figures, the elastic behavior of the mattress is calculated along a cranio-caudal axis, as illustrated in Figure 4.5 for five different polyurethane mattresses.

A MATLAB® script then calculates 20 linear spring coefficients, approximating these elastic properties at a fixed cranio-caudal distance of 0.1 m, as illustrated in Table 4.1 for...
the most relevant parts of the mattress. All parameters are implemented automatically in the model.

A second, and more elaborate, example is the Hamaso® Intermezzo® system, which is usually combined with a latex mattress. It consists of slats that are suspended on a rope (Figure 4.6). According to the manufacturer, adjustable pulleys between the slats ensure adequate support of the body in each region.

The system is modeled by Working Model® software, and a control panel is provided to adjust rope and pulley dimensions, as illustrated in Figure 4.7.

**FIGURE 4.6** Schematic representation of Hamaso® bed base.

**FIGURE 4.7** Model of Hamaso® pulley system.

### 4.1.1.3.3 Three-Dimensional Modeling

Similar AutoCAD® and Working Model 4D® procedures (see Section 4.1.1.2.3) have been developed to create a three-dimensional mattress model. Springs and dampers are positioned at a fixed distance of 0.1 m in the cranio-caudal and medio-lateral directions (in case of a supine sleep position), and similar procedures define dedicated spring and damper properties. Figure 4.8 illustrates the three-dimension model, which has not yet been put into practice due to a lack of elaborate three-dimensional subject models (see Section 4.1.1.2.3). The main added value of a three-dimensional model when compared to a 2.5D model is the possibility of introducing widthwise variations in the material characteristics.
4.1.1.4 Simulation of Subject-Sleep System

By joining the two models, a tool is provided to simulate the quasi-static interaction between the subject and the sleep system, as illustrated in Figure 4.9. As Working Model® software is able to process 40 frames per hour (for this multibody dynamics model) on a standard Pentium IV configuration, a typical simulation of 50 frames requires a considerable amount of CPU time.

Working Model® software further can provide output control panels in order to monitor the position, the velocity, and the acceleration of any point at any time. The quasi-static simulation can also be observed from any viewpoint, and all values are automatically transferred to Excel® files. As mentioned before, three-dimensional modeling requires a more elaborate subject model before the technique can be used for realistic simulations. A limitation to 2.5D (two-dimensional with a fixed height in the third dimension), therefore, is made, as illustrated in Figure 4.10. In order to define the
FIGURE 4.10 2.5D simulation.

TABLE 4.2 Polyurethane Characteristics
Simulated in 2.5D by Spring Coefficients (N/m)

<table>
<thead>
<tr>
<th>Body Part</th>
<th>Homogeneous</th>
<th>Firm Pelvis</th>
<th>Soft Pelvis</th>
<th>Soft Shoulder</th>
<th>Firm Waist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.252</td>
<td>0.252</td>
<td>0.251</td>
<td>0.251</td>
<td>0.251</td>
</tr>
<tr>
<td>Neck</td>
<td>0.261</td>
<td>0.261</td>
<td>0.260</td>
<td>0.258</td>
<td>0.261</td>
</tr>
<tr>
<td>Trunk 1</td>
<td>0.286</td>
<td>0.286</td>
<td>0.285</td>
<td>0.283</td>
<td>0.286</td>
</tr>
<tr>
<td>Trunk 2</td>
<td>0.272</td>
<td>0.273</td>
<td>0.274</td>
<td>0.264</td>
<td>0.271</td>
</tr>
<tr>
<td>Trunk 3</td>
<td>0.265</td>
<td>0.264</td>
<td>0.265</td>
<td>0.258</td>
<td>0.265</td>
</tr>
<tr>
<td>Trunk 4</td>
<td>0.259</td>
<td>0.257</td>
<td>0.257</td>
<td>0.252</td>
<td>0.258</td>
</tr>
<tr>
<td>Trunk 5</td>
<td>0.253</td>
<td>0.251</td>
<td>0.251</td>
<td>0.246</td>
<td>0.252</td>
</tr>
<tr>
<td>Trunk 6</td>
<td>0.247</td>
<td>0.245</td>
<td>0.245</td>
<td>0.241</td>
<td>0.247</td>
</tr>
<tr>
<td>Trunk 7</td>
<td>0.244</td>
<td>0.241</td>
<td>0.241</td>
<td>0.238</td>
<td>0.243</td>
</tr>
<tr>
<td>Trunk 8</td>
<td>0.257</td>
<td>0.257</td>
<td>0.253</td>
<td>0.256</td>
<td>0.257</td>
</tr>
<tr>
<td>Pelvis</td>
<td>0.251</td>
<td>0.251</td>
<td>0.248</td>
<td>0.250</td>
<td>0.251</td>
</tr>
</tbody>
</table>

optimal sleep system characteristics for a specific subject, only the final state of equilibrium is required.

Table 4.2 shows the simulation of polyurethane characteristics of five mattresses (see Section 5.1.3.2), by spring coefficients, in case of a 2.5D simulation.

4.1.1.5 Conclusion

This subsection described the multibody quasi-static two-dimensional and 2.5D modeling of a subject on a sleep system, used to provide on-site interactive customer information.
The model is able to demonstrate the support qualities of a certain sleep system for a particular subject, with a significant difference from other systems. Models corresponding to this minimal accuracy, however, take at least 2 hours of calculation time, and cannot be run in real time.

Further, realistic sleep system characteristics might be more composite, requiring more complex and more accurate (three-dimensional) modeling than is the case at present. These simulations are therefore excluded from real-time applications, and preference will be given to purely numerical simulations, as will be discussed further.

4.1.2 Linear Numerical Modeling

4.1.2.1 Technique

As graphic simulations are too time consuming to be applied in real time, the main aim of purely numerical models is to reduce the time to calculate the interaction between a sleep system and a subject. The graphical interface is minimized, and the representation of the model is less truthful (e.g., body parts are not connected), but the output of the simulations is generated fast and realistically by MATLAB® numerical software.

![Figure 4.11](image)

**FIGURE 4.11** Two-dimensional MATLAB® subject model.

First, straightforward two- and three-dimensional subject models are described, which are parameterized based on simple, easy-to-measure body dimensions. Several methods are described to calculate body contours and body mass distribution. Second, a mattress model is built and combined with the subject model to obtain a three-dimensional evaluation.

4.1.2.2 Subject Modeling

4.1.2.2.1 Two-Dimensional Modeling

By analogy with graphic modeling (see Section 4.1.1), the numerical subject model consists of several body blocks, excluding the influence of the arms and joining the legs into one simulation object, for a lateral and a supine sleep position. The number of blocks is variable, but each of the blocks has the same cranio-caudal dimension, and corresponds with one mattress block, as illustrated in Figure 4.11.
4.1.2.2 Parameterization

Second, the simplified model is shaped according to subject dimensions in order to estimate the position of the vertebral column in an accurate and individualized way. The most important properties are the body mass distribution, determining the level of body displacement into a sleep system, and the body contours, determining the actual position of the vertebral column, which is positioned in the middle of the trunk body blocks. Based on five basic body dimensions (shoulder width, waist width, pelvic width, body length, and body weight), a parameterized body mass distribution and appropriate body contours are generated by a MATLAB® script. Head cushion blocks are shaped to match head and neck dimensions, which is an important difference with graphic modeling. Further, all blocks are square and have fixed dimensions.

As for the approximation of body contours, results will be more accurate when a larger number of blocks is used. Figure 4.12 illustrates a typical contour calculation for a lateral sleep position, making use of 40 body blocks. All dimensions are displayed in a frontal cross section and with respect to the body midline.

Concerning body mass distribution, several calculation techniques can be applied. Literature expertise concerning this issue is very limited—the weight proportion of body parts with respect to total body mass is accurately described, but only for individual cases (Liu et al. 1971)—so mass distribution calculations will be based on body dimensions rather than on empiric formulas.

In the first step, body mass is distributed over the head, neck, trunk, upper leg, and lower leg region, according to literature guidelines (Björnstrup 1996, Erdmann and Gos 1990). This approximation is sufficiently accurate for the head-neck zone, but it results in large discontinuities between other body parts. In the second step, the total weight of the trunk and the legs is redistributed over the respective constituting blocks, in proportion to the area between the calculated body contours.

**FIGURE 4.12** Two-dimensional body contour approximation (frontal cross section).
4.1.2.2.3 Three-Dimensional Modeling

Similar procedures (cf. Section 4.1.2.2.2) are developed to create a three-dimensional subject model with MATLAB® software, adding midsagittal body dimensions. Figure 4.13 illustrates a typical contour calculation, displaying all dimensions in a midsagittal cross section with respect to the body midline.

Based on both midsagittal and frontal contour information, a more refined estimation of the mass distribution of the body can be made. In a first step, the weight of different body parts is distributed over the constituting blocks, in proportion to the volume of the respective parts. All volumes are shaped according to transversal cross-section data: trunk cross sections are approximated by ellipses based on midsagittal and frontal dimensions; circles approximate the cross sections of other body parts. This approximation is sufficiently accurate for all zones, except for the trunk zone; due to the presence of the lungs, the weight of the trunk is concentrated in the lower part of the trunk. In the second step, the total weight of the trunk is redistributed over the respective constituting blocks in proportion to the volume, but respecting different mass densities for the upper and lower trunk. When applying the resulting mass distribution guidelines to individual cases, as illustrated in Figure 4.14, a good correlation to literature data (Björnstrup 1996) is obtained.

![Figure 4.13: Two-dimensional body contour approximation (sagittal cross section).](image-url)
Finally, it should be noted that the described ellipse models are used only to calculate body mass distribution; the resulting subject simulation model remains square shaped.

4.1.2.3 Sleep System Modeling

4.1.2.3.1 Two-Dimensional Modeling

Square-shaped blocks represent the sleep system, each corresponding to one body block, and each having the same cranio-caudal dimension. The mobility of the blocks is limited to a vertical translation, while springs connect the blocks to the ground. The number of blocks is variable, and results will be more accurate when a larger number of blocks is used, but consequently the number of springs per sleep system block—and the distance between the springs—is variable, too, resulting in more complex spring coefficient calculations. Similar procedures are developed to create a three-dimensional sleep system model.

4.1.2.3.2 Parameterization

Sleep system characteristics can be adjusted by changing the spring properties and the number of blocks. The mass of the sleep system is only of secondary importance and, therefore, cannot be changed. An iterative algorithm calculates dedicated spring properties when the optimal sleep system characteristics for a specific subject are desired. When the best sleep system has to be chosen from a limited range, the most important task is to parameterize the model according to existing sleep system characteristics.

As an example, polyurethane mattresses are modeled for simulation purposes. These mattresses are subdivided in different zones, and the CTBA core stiffness is measured in a discrete number of points and interpolated over the entire bed surface (see Table 4.1). A
MATLAB® script then calculates a variable number of linear spring coefficients, approximating these elastic properties.

4.1.2.4 Simulation of Subject-Sleep System

In case the optimal sleep system characteristics for a specific subject are desired, a MATLAB® script defines the spring coefficients that are needed to support the vertebral column in the best possible way. Besides body characteristics, the number of blocks also has to be specified (40 sleep system blocks are used as standard value). Figure 4.15 illustrates the simulated optimal spring coefficients for a test subject.

![Figure 4.15](image1.png)

**FIGURE 4.15** Optimal spring coefficient values (N/m).

![Figure 4.16](image2.png)

**FIGURE 4.16** Vertebral column position.
When the best sleep system has to be chosen from a limited range, the most important task is to parameterize the model according to existing sleep system characteristics. Figure 4.16 illustrates the resulting simulated position of the vertebral column in a frontal cross section when the test subject is lying on a polyurethane mattress with a soft pelvic zone in combination with a rigid bed base. All distances are indicated in centimeters with respect to a fixed reference coordinate system.

Thanks to the limited calculation time (2 to 3 seconds per simulation), it is possible to simulate a relatively large sample of test persons ($n=20$) on polyurethane mattresses ($n=5$) within a reasonable amount of time and to calculate the mean square deviation of the simulated spine with respect to the measured spine for all spinal characteristics.

When comparing simulations and measurements (see Chapter 5), no exact absolute match is obtained, which could be expected since numerous simplifications are used in this simulation. Nevertheless, the same trend can be observed when comparing simulations and measurements. Sufficient accuracy is obtained to trace relative differences between the polyurethane mattresses and to choose correctly the sleep system with the best support qualities.

### 4.1.2.5 Conclusion

This subsection described the numerical modeling of a subject in combination with a sleep system, in order to demonstrate the support qualities of a certain sleep system with a significant difference from other systems. An accurate estimation of body contours and a consequent approximation of body mass distribution appear to be the main conditions to run an adequate simulation.

Further, no exact match is obtained between simulations and measurements; due to considerable simplifications, linear numerical models are not able—and will not be able—to provide an exact prediction of the behavior of the vertebral column on a sleep system. On one hand, the described estimation of the human body and the sleep system constitution could be enhanced by using a 2.5D model instead of a two-dimensional model (and a three-dimensional model instead of a 2.5D model), but on the other hand, the most contestable simplification—the negligence of nonlinearity—remains. Several sources of nonlinearity can be distinguished, including material nonlinearity (e.g., polyurethane mattresses) and nonlinear boundary conditions (e.g., contact analysis). For this purpose, finite element modeling will be needed, as will be discussed in the next subsection.

Sufficient accuracy, however, is obtained to trace differences between sleep systems. Numerical models, therefore, can be used to make a prompt but truthful conclusion concerning the degree of suitability of a sleep system for a subject.

### 4.1.3 Finite Element Modeling

#### 4.1.3.1 Technique

The finite element method (FEM) is a numerical technique that allows obtaining an approximate solution for the equations that govern the behavior of a physical system (e.g., a sleep system) that is externally loaded (e.g., by a subject) (De Roeck 1993). The
unknown field variable for which an approximate solution must be determined can be
displacement, temperature, or interface pressure. A finite element (F.E.) model is able,
therefore, to predict (1) the resulting shape of the vertebral column and (2) the pressure
distribution between a subject and a sleep system.

In a first attempt to simulate the behavior of the spine on a sleep system, only the final
position is considered as relevant. The calculation is reduced to a static mechanical
problem, and the unknown field variable is the displacement vector \( u \), which consists of
three components \( u_x, u_y, \) and \( u_z \), all functions of the \( (x,y,z) \) coordinates of a point:

\[
\mathbf{u}(x,y,z) = \begin{bmatrix} u_x(x,y,z) \\ u_y(x,y,z) \\ u_z(x,y,z) \end{bmatrix}
\]  

(4.1)

When a structure is externally loaded, three groups of equations must be fulfilled in order
to find a solution for the displacement field \( u(x,y,z) \): the equilibrium equations (the
relation between the external forces and the internal stresses), the compatibility equations
(the relation between displacement and strain), and the constitutive equations (the relation
between stress and strain). Combining the three groups of equations yields a system of
coupled differential equations for the unknown displacement \( u \), which must be solved
numerically. A possible numerical solution method is the method of weighed residuals,
which will yield an integral equation that can be rewritten as a system of linear equations:

\[
K \mathbf{a} + \mathbf{f} = \mathbf{0}
\]

(14.2)

\( K \) is called the stiffness matrix, \( \mathbf{f} \) the force vector, and \( \mathbf{a} \) is the vector that contains the
unknown constants that must be determined. The elements of \( K \) and \( \mathbf{f} \) are found by
numerically evaluating integrals over the domain \( \Omega \) (i.e., the domain for which a solution
must be calculated) and its boundaries.

The finite element method can be considered as a special case of the method of
weighed residuals; the domain \( \Omega \) is now divided in subdomains \( \Omega_e \), called elements,
which are usually basic shapes, like triangles and quadrilaterals (two-dimensional) or
tetrahedrons and hexahedrons (three-dimensional). Nodes are defined on the edges—and
sometimes in the middle—of the elements, and the system stiffness matrix is assembled
from the element stiffness matrices. Once the system stiffness matrix is assembled, the
linear system of equations can be solved. More information on this methodology can be
found in literature (De Roeck 1993).

In order to reduce computation time and memory requirements, the development of
efficient solvers—either direct or iterative—is of major importance. Direct solvers
assemble the entire system stiffness matrix and calculate a solution by means of
numerical techniques. Although these methods are usually very stable and accurate, they
have the disadvantage of requiring a large amount of memory. Iterative solvers are based
on conjugate gradient methods and allow the solution of very large systems at a reduced
computational cost but may lead to slow convergence in the case of ill-conditioned
systems.

A problem is called linear if the stiffness matrix in the second equation remains
constant throughout the analysis (i.e., the relation between force and displacement is
linear. In reality, most physical systems exhibit nonlinear behavior. Three sources of nonlinearity can be distinguished: material nonlinearity (results from the nonlinear relation between stresses and strains, e.g., polyurethane mattresses), geometric nonlinearity (results from the nonlinear relation between strains and displacements on the one hand and stresses and forces on the other hand), and nonlinear boundary conditions (boundary conditions changing during analysis, e.g., contact analysis). Depending on the amount of nonlinearity, the solution of a nonlinear problem typically requires a number of load increments that are solved iteratively.

4.1.3.2 Subject Modeling

4.1.3.2.1 Two-Dimensional Modeling

At first, a parametric 2D finite element model of the combination individual-mattress is developed to predict the curvature of an individual’s vertebral column when lying on a specific sleep system (Haex and Kennis 1995). The finite element analysis software used (MARC®/MENTAT®) is particularly suited for nonlinear problems. Although previous studies of the body-sleep system combination are not found in literature, studies in the early seventies observing and modeling spinal behavior subjected to impact (Luo and Goldsmith 1991), such as in an ejector seat (Orne and Liu 1971), are helpful. Further, more recent finite element models are constructive (Goel and Gilbertson 1995), but too detailed in modeling the vertebral column only. Consequently they cannot be implemented in a total body-on-sleep system analysis.

On one hand, the aim of the resulting model is to represent the deformation of the spine; the different lumbar and thoracic vertebra should therefore be modeled independently. On the other hand, there is no need to model the intervertebral disks (e.g., the nucleus pulposus) and the vertebrae (e.g., the processi transversi) on an anatomical level, because dedicated finite element models exist (Goel and Gilbertson 1995) to calculate the stresses and strains in these parts, starting from the overall deformation of the spine. Consequently, the resulting model represents the body as a set of quadrilateral elements, each with specific simplified and parameterized geometric and material

![FIGURE 4.17 FE model of a subject: Young’s modulus (GPa=10^9 N/m).]
properties (Notelaers and Saye 1996), which are linear at a first stage and nonlinear at a second stage (see Section 4.1.3.2.3). Figure 4.17 illustrates a supine sleep position, with each grayscale value representing different linear elastic material properties (e.g., Young’s modulus).

The human skeleton is assumed to be rigid and is represented by a simplified shoulder and pelvic girdle, a rib cage, head, and legs, all represented by a set of quadrilateral elements (Haex et al. 1998). Further, the vertebra and intervertebral disk sections are represented as a succession of quadrilateral elements, with stiffness parameters that are obtained from literature (Schulz et al. 1973). Finally, soft tissue stiffness parameters are assumed to remain constant over the body length and are approximated by linear properties. Weight distribution characteristics and geometrical properties are individualized and will be discussed in the next paragraph.

4.1.3.2.2 Parameterization

First, a three-dimensional parameterized CAD (Computer Aided Design) model of the spine is constructed using Unigraphics® and Grip® (see Figure 4.18). The CAD model is based on anthropometrical data of the vertebral column in an upright position. (The first section of Chapter 3 describes how these data are obtained).

Second, an accurate estimation of the entire body configuration is calculated from a limited number of well-chosen body parameters (see Section 4.1.2), and a CAD model of a subject is constructed, as illustrated in Figure 4.19.

Finally, the geometrical CAD output is transferred to a finite element model, adding material characteristics and body weight distribution, using the same procedures as for numerical modeling. Two 2D cross sections—one frontal for a lateral sleep position and one sagittal for a supine sleep position—are made, as illustrated in Figure 4.20.

By analogy with numerical modeling, the 3D CAD model is used only—at least at this point—to provide an adequate estimation of the body mass distribution; the actual parameterized subject simulation model (see Figure 4.17) remains two-dimensional.
Stimulated by the major step forward that digital animation has taken the last couple of years, a larger number of derived and/or related techniques have made considerable progress. The application of these 3D techniques to sleep research is, however, still in its infancy. Consequently the description of 3D FEM will be limited to a depiction of the overall methodology.

3DStudioMax® software is able to build and to parameterize a geometric model of a subject in three dimensions, while third-party software is available to provide standard anatomical models. The main advantages of 3DStudioMax® are its open structure (C++ subroutines, import/export formats, etc.) and the fact that the geometry of the body can be reproduced accurately based on basic anthropometrical parameters, which is important for an estimation of body weight distribution.

Further, surface meshes are standard available for both male and female subjects, with detailed skeleton information linked to it. In a first step these meshes are modified in an interactive way, in order to match specific individual parameters. The model can also be adjusted to the body posture that has to be studied (e.g., lateral sleep position). In a second step, the surface mesh is exported—through DXF, the typical Autocad® format—to be implemented in MARC® finite element software. A 3D volume mesh is then generated, and material properties and weight properties are added, by analogy with 2D models.

The main disadvantage of this technique is interfacing: degrees of freedom (e.g., freedom of movement of the shoulder articulation) and positions of internal nodes (e.g., vertebral column) cannot be transferred automatically to MARC®.
4.1.3.3 Sleep System Modeling

On one hand, the model should be able to represent the overall deformation of the sleep system; its surface should be included in the model. On the other hand, there is no need to model all parts of the sleep system (e.g., springs), because there is no interest in the stresses and strains in these components. If interest in this arises, dedicated mechanical models are available to analyze the behavior of these parts, starting from the overall deformation of the sleep system.

As a consequence, the sleep system model is relatively uncomplicated when compared to the model of the human body. The only parameters that matter are the (nonlinear) mattress and bed base stiffness parameters, which are obtained by measuring force-displacement characteristics according to international standards (CTBA and LGA [DIN 1991]), as described in Chapter 5. However, the problem with the software (MARC®/MENTAT®) is that it is not able to deal with these standards: only typical engineering stress/strain determinants (e.g., Young’s modulus) can be implemented. Curve-fitting software is coupled with MARC® to extract these parameters from a stress-strain or force-indentation characteristic. At the first stage, a linear approximation was made (see 1st approximation on Figure 4.21), consisting of a linear elastic part and an ideal plastic plateau. At the second stage, a second-order model approximates the curve (see 2nd approximation on Figure 4.21).

All tests measure force (F) at a constant indentation rate; however, due to large deformations during compression, the mattress cross section significantly increases with respect to the initial mattress cross section (A₀), so that the so-called engineering stress (F/A₀) no longer adequately estimates the real stress (F/A). The real stress-strain behavior of the polyurethane material, therefore, is determined iteratively, using dedicated finite element models.

Compression tests are modeled using an initial estimation of the stress-strain properties based on the engineering stress, in order to compare the resulting force-indentation behavior to the actual test values. Further, this stress-strain input is adjusted iteratively until the modeled forces-displacements coincide with the test values. Two

![FIGURE 4.21 Approximation of the stress-strain behavior of a polyurethane mattress.](image)
different axi-symmetrical finite element models are built for this purpose: one for simulating tests on complete polyurethane mattresses (see Figure 4.22, left), and one for simulating tests on polyurethane samples (see Figure 4.22, right). At some locations the element mesh is refined to cope with large deformations.

4.1.3.4 Combined Simulation of Subject and Sleep System

At the first stage, a linear type of element (arbitrary plane-strain four-node quadrilateral, element type # 11 in MARC®) is used for carrying out two-dimensional analyses. At the second stage, a different type of element is used (arbitrary plane-strain four-node quadrilateral, Hermann formulation, element # 80 in MARC®) to reckon with the nonlinear behavior of polyurethane and with contact. The main disadvantage when compared to distorted eight-node elements (which are not suited for contact analyses) is the need for a fine mesh (see Figure 4.22). Starting from nodal displacements and reaction forces, the resulting vertebral curvature and the resulting interface pressures are calculated. One can focus on mattress deformations or on spinal behavior, as is in Figure 4.23.

When the best sleep system has to be chosen from a limited range, the test subject is simulated on different sleep systems, as illustrated in Figure 4.24. Further, general conclusions can be made concerning stiffness distribution, coinciding well with measurement values (see Chapter 5): for most people the hip zone of the mattress must be stiffened to prevent the pelvis from canting forward in a supine sleep position; the shoulder zone must be soft to prevent a scoliosis in a lateral position.
4.1.3.5 Conclusion

This section described the finite element modeling of a subject in combination with a sleep system, in order to demonstrate the support qualities of a certain sleep system with a significant difference from other systems. Due to the combination of different sources of nonlinearity—both contact and large deformations—convergence problems may arise resulting in a time-consuming process of adjusting the analysis parameters.

Looking at the influence on the resulting spinal deformation parameters (such as the lumbar lordosis), it appears that, at least at the time of the simulations, the sensitivity to parameters that are not part of the model (e.g., contact analysis parameters) can be of a similar magnitude (with relative changes up to 20%) when compared to the sensitivity of the model parameters (e.g., material properties).

On one hand, the current FE models are considerably simplified and not accurate enough (e.g., body material properties) to obtain an exact match between simulations and measurements. Further, the sensitivity analysis shows that the software used is—or was—not satisfactory to solve the postulated models.

On the other hand, finite element models are able to handle nonlinearity, which was not the case for the existing numerical models. Thanks to this nonlinearity, finite element models will be able to provide an accurate prediction of the behavior of the vertebral column on a sleep system, if all value input is carried out elaborately and correctly.

Sufficient accuracy, however, is obtained to trace the differences among a very limited number \((n=5)\) of sleep systems. The current finite element models, therefore, can be used to make a valuable conclusion toward the degree of suitability of a sleep system for a subject.
4.1.4 Neural Networking

4.1.4.1 Technique

A neural network is a nonlinear system that can be trained to reproduce an input-output pattern. Its basic entities, neurons, are combined into layers establishing a network mechanism. An artificial neural network, consisting of typically 10 to 100 neurons, aims to imitate the structure of the human brain, which is a biological neural network (Gurney and Wright 1996) consisting of about 100 billion neurons. As illustrated in Figure 4.25, each neuron is able to simulate basic input-output behavior: an input \( p \) is multiplied by a weight \( w \) and summed with an offset \( b \); the result \( n \) then is transposed to an output \( a \) by a (nonlinear) transfer function \( f \), which is able to attribute nonlinear behavior to the neuron.

Biological neurons are able to assimilate a more complex input than the one described below; artificial neurons can imitate this behavior by applying several inputs at the same time. As illustrated in Figure 4.26, a summation is made of the offsets and of the inputs with the respective weights.

\[
a = f(wp+b)
\]

**FIGURE 4.25** Artificial neuron with one input.

\[
a = f(Wp+b)
\]

**FIGURE 4.26** Artificial neuron with vector input.
Several neurons are combined in parallel to build up layers. These layers then establish an entire artificial neural network, as illustrated in Figure 4.27.

The first and most important phase of establishing a neural network is the training sequence: all neuron parameters (weights, offsets, etc.) are adjusted iteratively to fulfill the imposed input-output relation. In the second phase the network should be able to predict correct output values for new input values (i.e., values that were not used during the training sequence).

Weights and offsets are adjusted by applying known input-output pairs. These couples can be implemented incrementally, adapting the network parameters after each input-output couple or, in batch, changing the parameters only once, subsequent to the application of all training couples. Incremental training is used only for dynamical networks, so this study focuses on batch processing.

Further, backpropagated learning is used, starting with the output layer and gradually propagating backward to the input layer. It is most simply implemented by the gradient descent algorithm, modifying the weights and offsets in the direction of the performance function that decreases most significantly (the negative gradient). The most commonly used performance function is the mean squared error (MSE) between the output of the network and the expected output of the target. Every iteration of the gradient descent algorithm can be written as follows (with $x_k$ a weight/offset vector, $\alpha_k$ the learning rate, and $g_k$ the gradient).

$$x_{k+1} = x_k - \alpha_k g_k$$

(4.3)

When the learning rate $\alpha_k$—determining the magnitude of the parameter changes—is too small, the neural network will take too much time to reach a solution. When it is too large, the network might rush past the correct solution by taking too large steps. Several variants of the gradient descent algorithm can be applied: gradient descent variable learning rate, resilient backpropagation, conjugate gradient propagation, Quasi-Newton or Levenberg-Marquardt propagation. Table 4.3 compares these five different training methods for a 1-10-1 network (i.e., a network with 1 neuron in the first layer, 10 neurons in the second layer, and 1 output neuron) that is trained with 41 input-output couples until a quadratic relative error of 0.01 is reached (Demuth and Beale 1994). In addition to calculation time, the number of epochs is compared, representing the single application of
a complete data set and a consequent adjustment of the network parameters. Although the Levenberg-Marquardt algorithm is both the fastest and the most efficient one, other algorithms might give better results in some situations.

**TABLE 4.3** Comparison of Different Training Algorithms

<table>
<thead>
<tr>
<th>Technique</th>
<th>Time</th>
<th>Epoch #</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Variable learning rate</td>
<td>57.71</td>
<td>980</td>
</tr>
<tr>
<td>2 Resilient backpropagation</td>
<td>12.95</td>
<td>185</td>
</tr>
<tr>
<td>3 Conjugate gradient</td>
<td>16.06</td>
<td>106</td>
</tr>
<tr>
<td>4 Quasi-Newton</td>
<td>10.86</td>
<td>44</td>
</tr>
<tr>
<td>5 Levenberg-Marquardt</td>
<td>1.87</td>
<td>6</td>
</tr>
</tbody>
</table>

From De Craecker, W. and Janssens, G., Bepaling van een optimaal slaapsysteem op basis van anthropometrische kenmerken—vergelijking tussen neurale netwerken en mechanische modellen, Department of Agricultural Machinery and Processing, Catholic University, Leuver, Antwerp, Belgium, 2001.

![Artificial neural network simulation.](image)

**FIGURE 4.28** Artificial neural network simulation.

**TABLE 4.4** Input Matrix

<table>
<thead>
<tr>
<th>Head Zone (M1)</th>
<th>Head Zone (M2)</th>
<th>Head Zone (M3)</th>
<th>...</th>
<th>Head Zone (M5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder zone (m1)</td>
<td>Shoulder zone (m2)</td>
<td>Shoulder zone (m3)</td>
<td>...</td>
<td>Shoulder zone (m5)</td>
</tr>
<tr>
<td>Waist zone (m1)</td>
<td>Waist zone (m2)</td>
<td>Waist zone (m3)</td>
<td>...</td>
<td>Waist zone (m5)</td>
</tr>
<tr>
<td>Pelvic zone (m1)</td>
<td>Pelvic zone (m2)</td>
<td>Pelvic zone (m3)</td>
<td>...</td>
<td>Pelvic zone (m5)</td>
</tr>
<tr>
<td>Sex (s1)</td>
<td>Sex (s1)</td>
<td>Sex (s1)</td>
<td>...</td>
<td>Sex (s20)</td>
</tr>
<tr>
<td>Weight (s1)</td>
<td>Weight (s1)</td>
<td>Weight (s1)</td>
<td>...</td>
<td>Weight (s20)</td>
</tr>
</tbody>
</table>
Neural networks are able to simulate measurements of a subject on a sleep system (De Craecker et al. 2001). The data set provided by the second measurement set (see Section 5.2) is taken as an example. A group of 20 subjects—a selection of those demonstrating a significant difference between the best possible sleep system and other systems—is used as a training set in combination with five polyurethane mattresses. As deformations of the spinal column in a frontal projection are most relevant, network training will concentrate on these output parameters at the first stage. Input parameters consist of six anthropometrical parameters, and four sleep system characteristics are included, as illustrated in Figure 4.28.

As batch training requires a matrix structure, all data are transformed into this format, resulting in the $10 \times 100$ input matrix illustrated in Table 4.4. Ten rows represent the four mattress characteristics and the six subject parameters mentioned earlier; 159 columns merge all possible combinations of subjects (s1-s20) and sleep systems (m1-m5).

The output matrix ($3 \times 100$, illustrated in Table 4.5) yields the output values for three frontal parameters of the vertebral column: $P_6$ (the mean square deviation of the spine to the frontal projection of the least square line, see Section 5.1.2.1 for a detailed description), $P_7$ (the mean deviation angle of the spine with respect to the reference coordinate system), and $P_8$ (the angle between the thoracic and lumbar areas of the spine, see Section 5.1.2.1). The expected output values are represented in three rows, and the columns coincide with the input matrix values, each representing the expected output of a combination of a subject (s1–s20) and a sleep system (m1–m5).

Further, the entire group is subdivided into a training set and a test set, the latter taking one third of the entire group. At first, a 3–3 architecture is used, with three neurons in the both the input and the output layers, in combination with the Levenberg-Marquardt training algorithm (implemented in MATLAB®), calculating a predetermined number of epochs. In the second step, optimizing the architecture enhances the performance of the network; increasing the number of neurons in the hidden layer (up to 7 or 8) will improve the adjustment to the training set. This, however, does not necessarily imply an

<table>
<thead>
<tr>
<th>Length (s1)</th>
<th>Length (s1)</th>
<th>Length (s1)</th>
<th>…</th>
<th>Length (s20)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Width (s1)</td>
<td>Shoulder Width (s1)</td>
<td>Shoulder Width (s1)</td>
<td>…</td>
<td>Shoulder Width (s20)</td>
</tr>
<tr>
<td>Waist width (s1)</td>
<td>Waist width (s1)</td>
<td>Waist width (s1)</td>
<td>…</td>
<td>Waist width (s20)</td>
</tr>
<tr>
<td>Pelvic width (s1)</td>
<td>Pelvic width (s1)</td>
<td>Pelvic width (s1)</td>
<td>…</td>
<td>Pelvic width (s20)</td>
</tr>
</tbody>
</table>

**TABLE 4.5 Output Matrix**

<table>
<thead>
<tr>
<th>$P_6$ (p1m1)</th>
<th>$P_6$ (p1m2)</th>
<th>…</th>
<th>$P_6$ (p20m5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_7$ (p1m1)</td>
<td>$P_7$ (p1m2)</td>
<td>…</td>
<td>$P_7$ (p20m5)</td>
</tr>
<tr>
<td>$P_8$ (p1m1)</td>
<td>$P_8$ (p1m2)</td>
<td>…</td>
<td>$P_8$ (p20m5)</td>
</tr>
</tbody>
</table>
improvement of the test group results, as too high a number of neurons (more than 8 in this example) will over-train the network. Also the effect of the initial parameter values (weights, offsets, etc.) on the performance of a network should not be underestimated. It is advisable to calculate the average values over several training sequences (preferably 10), each with random weights and offsets.

Next to so-called “v-fold cross-validation” (Burman 1989), the easiest way to assess a network is by performing a regression analysis between the simulated output values and the expected values, as illustrated in Figure 4.29. A MATLAB® procedure calculates the correlation coefficient between the simulated and the expected outputs.

FIGURE 4.29 Regression analysis for parameter P₈.

As illustrated in Figure 4.30, some values strongly differ from their expected outcome.

It is clear that the result is still unsatisfactory, even after thoroughly optimizing network parameters (architecture, training function, etc.).

FIGURE 4.30 Expected vs. simulated values for parameter P₈.
4.1.4.2 Conclusion

The existing neural networks were not able to simulate measurements of a subject on a sleep system, because not enough measurement data (sets 1 and 2, see Section 5.2) were available to train the network at the moment it was conceived. Plenty of input-output pairs can be applied, but only those choosing an optimal sleep system with a significant difference from other systems can be used. Also, a larger number of basic anthropometrical input values are needed (e.g., shoulder height) to estimate a subject’s anthropometries with higher accuracy.

In the meantime, the third data set (see Chapter 5) has become available, with larger differences between the sleep systems and more accurate decisions, which is exactly what is needed for better results with neural networks. Although this sounds very promising, it is not possible to elaborate on it within the framework of this study.

4.2 General Conclusion

Graphic modeling of a subject on a sleep system can be considered successful, as it is able to visualize the support qualities of a certain sleep system for a subject, in an accurate and parameterized way. The only minus point at present is the calculation time, so for real-time applications preference is given to pure numerical simulations, which are able to run simulations within a few seconds.

The precision of linear numerical models is dependent on an accurate estimation of body contours, which can be obtained relatively simply, and an approximation of body mass distribution, which requires complex procedures. As a consequence, considerable simplifications are made, giving rise to numerical models not being able to provide an exact prediction of the behavior of the vertebral column on a sleep system. Sufficient accuracy, however, is obtained to trace differences between sleep systems. Numerical models, therefore, can be used to make a prompt but truthful conclusion toward the degree of suitability of a sleep system for a subject.

Finite element models are able to simulate nonlinear behavior, but the combination of different sources of nonlinearity may provoke convergence problems resulting in a time-intensive process of adjusting the analysis parameters. At present, FE models are considerably simplified and not accurate enough to obtain an exact match between simulations and measurements, as is also the case for numerical modeling. On the other hand, if value input were carried out elaborately and correctly, finite element models would be able to provide an accurate prediction of the behavior of the vertebral column on a sleep system. Sufficient accuracy, however, is already obtained to trace differences between sleep systems.

The use of neural networks for measurement simulation is not successful at the moment, as not enough measurement data are available to train the network. On the other hand, neural networks will offer an insurmountable measurement simulation tool, when a data set comes available that satisfies all requirements.

When modeling a subject on a sleep system, the most important output is the resulting displacement of rigid bodies with respect to each other (e.g., spine segments). As a result, multibody modeling (either with or without a graphical interface) will be most adequate; next to rigid body motion, estimations can be made of the resulting global deformation of
soft tissues and of the force distribution, which allows analysis of the effect of the mattress properties and of the sleeper’s posture. A finite element type of analysis, however, might be needed in the future, when pressure and shear stress profiles at the human-bed interface or in the vertebral discs would be needed. But a combination of FEM modeling and multibody modeling into one model should be avoided, if possible, as it would make the entire model too complex. As a solution, complex global modeling (implying a large number of parameters that might be difficult to validate) can be avoided by splitting the model into a simple multibody model of a complex global structure (the entire human body) and a complex FE model of a simple local structure (e.g., intervertebral disks). The complex model can be used in two ways:

1. To extract a basic parameter set (e.g., a limited set of parameters to model the behavior of an intervertebral disk), which can be used as an input for the simple multibody model.
2. To analyze stresses and strains in detail (e.g., in an intervertebral disk) by using the output of the simple multibody model (e.g., posture) as an input for the complex model.

As a final conclusion, the feasibility of replacing or completing complex experimental work by simulating measurements is clearly demonstrated. Nevertheless, simulation output data should always be interpreted with care, especially when large extrapolations are made with respect to the actual data set that was used to build the model, no matter whether it concerns graphic, numerical, finite element, or neural network modeling.

References


De Craecker, W. and Janssens, G., Bepaling van een optimaal slaapsysteem op basis van anthropometrische kenmerken—vergelijking tussen neurale netwerken en mechanische modellen, Department of Agricultural Machinery and Processing, Catholic University, Leuver, Antwerp, 2001.


5
The Impact of Custom-Made Bed Design on Back Support

A synergy of psychological, physiological, and physical conditions affects the mental and physical quality of sleep, as described throughout Chapters 1 and 2. The most important physical component is the sleep system (i.e., mattress+support structure+head cushion). It mainly affects our physical condition during the night and, consequently, also during the day. Due to an insufficiently adapted sleep system, the human body—especially the vertebral column—is often supported unsatisfactorily, resulting in low back pain or sleeping disorders. Since both body dimensions and body weight distribution have an important influence on the position of the vertebral column on a sleep system, every person ideally needs an individually adapted sleep system. In practice, however, this is not profitable, given manufacturing techniques at present. People are, therefore, subdivided into population classes, and a range of sleep systems is optimized in accordance with these classes.

As illustrated in Chapters 3 and 4, several measurement techniques and modeling methods are able to evaluate the alignment of the spine during bed rest by comparing the spine position on a sleep system with the spine position during upright standing. This chapter first discusses how these measurements fit into the methodology to gain a progressively clearer insight into the impact of bed design on spine support. Starting from guidelines generated by simplified measurements, the influence of different types of body support on spine support is studied in depth through detailed measurements, while gradually focusing on the relation with anthropometrical properties. Second, this chapter describes measurement results, and how they contribute to the determination process of the optimal sleep system for each individual or for each population class.

5.1 Methodology

In order to picture the impact of bed design on spinal support, especially in relation to anthropometrical properties, not only “output” parameters should be measured (e.g., the behavior of the vertebral column). All causal “input” parameters have to be incorporated as well, including both personal and sleep system characteristics, to perform a thorough statistical analysis. The first subsection describes the contributing factors—both input and output parameters—and how they are acquired.

The second subsection further illustrates how spinal alignment is evaluated during bedrest by comparing the spine position on a sleep system with reference values, and how a correlation is established between anthropometrical characteristics and optimal sleep system properties. Based on this knowledge, people can be subdivided into several
population classes in order to allocate a suboptimal but feasible solution to every subject. Finally, the third subsection of the methodology section describes the measurement sequence to be followed, and how it contributes to a progressively clearer insight into the impact of bed design on spine support.

5.1.1 Data acquisition

In order to obtain a complete picture when analyzing the vertebral column of a subject on a sleep system, both input and output parameters have to be monitored, as illustrated in Figure 5.1. Input parameters are registered before recumbent testing and can be subdivided into two classes: anthropometrical characteristics and sleep system properties. Output parameters are registered during recumbent testing and, as this book is concentrating on back problems, mainly affect the position and orientation of the spine.

5.1.1.1 Input Data: Subject and Object Characteristics

5.1.1.1.1 Acquisition of Anthropometrical Characteristics

When comparing people with diverse builds, body dimensions and body weight distribution differ strongly. Since these parameters have an important influence on the position and the orientation of the vertebrae of a subject in a lying posture—and consequently on phenomena such as low back pain (Dolan et al. 1988)—they should be estimated accurately and preferably within a reasonable space of time (e.g., to enable the implementation of these measurements in a retail environment). Measurements of a midsagittal and

![FIGURE 5.1 Data acquisition flowchart.](image-url)
a frontal body contour provide the information necessary—and satisfactory—to obtain the required body characteristics. In the first step, the entire body is approximated, starting from a limited set of essential body dimensions that are easy to quantify. In the second step, a volumetric model estimates the body weight distribution based on the previously derived anthropometrical characteristics.

When monitoring the vertebral column, major individual profile differences are observable (Pheasant 1991). For example, some subjects have a smooth lumbar lordosis and a flat back surface (as illustrated on the left of Figure 5.2), while others have a pronounced back surface caused by a hyperlordosis, as depicted on the right of Figure 5.2. These spinal curvature characteristics are used as reference values in order to evaluate the spine on a sleep system; consequently, they have to be monitored individually. Measurements of the midsagittal body contour provide the information that is necessary—and satisfactory—to obtain the required spinal characteristics.

At the first stage of the measurement process, a laser system was built to measure anthropometrical parameters, in order to implement an individual’s entire geometry in a statistical model, which is explained further. The system consists of a laser transmitter-receiver that slides automatically along a vertical axis while measuring the horizontal distance \(d\) (±1 mm) between the transmitter and the subject, hence providing contour data on a frontal body cross section, as illustrated in Figure 5.3. Distances are measured 30 times a second with a vertical transmitter velocity of 0.18 m/s; the absolute error on the vertical position of the transmitter is 1 mm.

As pictured in Figure 5.4, the same equipment is also used to determine thoracic kyphosis and lumbar lordosis of the spine by measuring a mid-sagittal body contour (see Section 1.1.1.1 for the anatomy of the spine). As for frontal body contour measurements, the subject is instructed to adopt a straight and stable upright position while distances are measured with the same vertical transmitter velocity and accuracy as for frontal cross-section measurements.
Repeatability tests demonstrate that posture differences result in a relatively high error on the resulting coordinates (±2 mm). Both types of measurements, therefore, are performed five times on every person to enhance the estimation error of the measured parameters with a factor of $1/\sqrt{5}$.

As discussed in Chapter 3, white-light raster line triangulation (Drerup and Hierholzer 1994) was developed in combination with active contour analysis (Huysmans et al. 2000) at the second stage of the research process. Thanks to this technical progress, reference measurements of thoracic kyphosis and lumbar lordosis of the spine can be performed with the same flexible equipment used for lying postures (illustrated in Figure 3.21, see Section 3.2.2.1). Measurements in an upright standing position can be included as a reference run at the beginning of each measurement sequence, as pictured in Figure 5.5.

As a result of the growing insight into the relation between body dimensions and optimal mattress characteristics, the number of elemental body dimensions can be limited without doing harm to the accuracy of the estimation of the complete body figure.

At the first level, a relatively large group of anthropometrical parameters is defined in order to characterize the entire body constitution of a person. Pheasant (1996) defined 36 body parameters for this purpose and, more recently, 40 parameters (see Table 5.1) were defined in the framework of the CAESAR Project (Civilian American and European Surface Anthropometry and Resource Research Project) (Robinette et al. 1999). This project is generating
FIGURE 5.5 Flexible WLRT equipment for measurements in an upright position.

TABLE 5.1 Anthropometrical Parameters

<table>
<thead>
<tr>
<th>Circumference Measures</th>
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</thead>
<tbody>
<tr>
<td>Head circumference</td>
<td>Arm—scye circumference</td>
<td>Neck base circumference</td>
</tr>
<tr>
<td>Waist circumference</td>
<td>Trunk circumference</td>
<td>Thigh circumference</td>
</tr>
<tr>
<td>Chest girth</td>
<td>Ankle circumference</td>
<td>Circumference under bust</td>
</tr>
<tr>
<td>Hip circumference</td>
<td>Hand circumference</td>
<td>Bust—chest circumference</td>
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<table>
<thead>
<tr>
<th>Height Measures</th>
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</tr>
</thead>
<tbody>
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<td>Stature</td>
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<td>Eye height</td>
</tr>
<tr>
<td>Sphyrion height</td>
<td>Malleolus height</td>
<td>Popliteal height</td>
</tr>
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<td>Pelvic height</td>
<td>Crotch height</td>
<td>Knee height</td>
</tr>
<tr>
<td>Waist height</td>
<td>Elbow height</td>
<td>Chest height</td>
</tr>
<tr>
<td>Infra-orbital height</td>
<td>Acromial height</td>
<td>Cervical height</td>
</tr>
<tr>
<td>Axillary height</td>
<td>Supra-ternal height</td>
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<table>
<thead>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Face length</td>
<td>Spine—shoulder</td>
<td>Acromion-olecranon length</td>
</tr>
<tr>
<td>Spine—elbow</td>
<td>Waist front length</td>
<td>Femoral epicondyle-lateral malleolus</td>
</tr>
<tr>
<td>Spine—wrist</td>
<td>Radiale—stylion</td>
<td>Menton—sellion length</td>
</tr>
<tr>
<td>Arm inseam</td>
<td>Hand length</td>
<td>Buttock to trochanter length</td>
</tr>
<tr>
<td></td>
<td>Crotch length</td>
<td>Buttock—knee length</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Width Measures</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Head width</td>
<td>Inter-pupillary dist.</td>
<td>Bi-trochanteric hip width</td>
</tr>
<tr>
<td>Bitragion width</td>
<td>Bi-zygomatic width</td>
<td>Bi-acromial shoulder width</td>
</tr>
</tbody>
</table>
a database of human physical dimensions for men and women of various weights, between the ages of 18 and 65. A total of 2500 people in the United States and 2500 in Europe have been measured, with the Dutch Nedscan Project (Daanen 1995) being part of it. The project aims at a full anthropometrical characterization, independent from specific applications.

At the second level, the number of parameters can be limited by making a selection for specific purposes, which can be done by using Cleopatra (Paquet et al. 2000) software. Based on the CAESAR dataset, it describes human bodies according to shape, anthropometrical, and demographic data and is able to extract valuable information from the anthropometrical database. Cleopatra is used for applications like car ergonomics, virtual mannequins, and fashion. Another selection possibility is to use the data of the garment industry (Febeltex 1999), which is close to the aimed application.

At the third level, a selection to 18 parameters can be made, because good significant correlations (Febeltex 1999) exist among several parameters (e.g., ankle height, popliteal [or knee cavity] height, and pelvic height). Omitting dependent parameters results in the heuristic selection that will be used for this work: body length, body weight, and the width, height, depth, and perimeter of the body at four specific locations (see Figure 5.6).

Thanks to this simplification, continuous laser measurements of entire body contours (both frontal and sagittal) are no longer necessary. The laser can be replaced by a digital goniometer (±0.5°) or a digital sliding caliper (±0.1 mm) mounted on a similar vertical slide (±1 mm). With this equipment, body width can be measured fast, accurately, and automatically in any transversal direction and at several body heights (e.g., at the shoulders). Figure 5.6 illustrates the four main locations at which the majority of the determining parameters are measured. Complementary principal body characteristics (body height, body weight, and body perimeters) are measured with the same equipment, with a balance (±0.25 kg) and with a tape measure (±1 mm), respectively.
Sometimes a final selection (at level four) is needed when there are specific limitations (e.g., availability of measurement equipment). Typically, three parameters remain: body length, body weight, and body contour (which is based on pelvic width, waist width, and shoulder width). In the near future, this set will be used in the garment industry and retail, which is now using only one measure to characterize a person. This might be an extra advantage for the sleep system industry as well, as people will be more aware of their body measures and a better fit can be achieved.

Starting from the basic anthropometrical characteristics used throughout this study (level three), advanced parameters can be calculated to estimate an individual’s body build in a more realistic way (e.g., by indicating the weight distribution of the trunk). In addition to simple multiplications—or quotients—of the measured parameters, the volume of (a part of) the trunk and the area of (a part of) a transversal trunk section are estimated.

The method used to approximate a transversal section area makes a linear interpolation between the measured contour points and calculates the area between the

**FIGURE 5.6** Width measurements at four body heights.

**FIGURE 5.7** Anthropometrical properties.
resulting estimations of the body contours. Figure 5.7 illustrates this methodology for the upper trunk area. Body volumes are estimated in an analog way—but in three dimensions—by approximating the trunk volume with a succession of truncated cones.

5.1.1.1.2 Acquisition of Bed Characteristics

In order to establish a correlation between anthropometrical characteristics and optimal sleep system properties, the latter have to be defined in detail. As explained in Chapter 2, material density mainly affects fatigue resistance, while material elasticity—and the combination of materials with a different elasticity—guarantees correct support of the human body. Due to the less important relation with spine support, material density measurements will not be included.

Furthermore, it is possible to obtain the required elastic characteristics with several material types by producing or adjusting them correctly: the elasticity of latex mattresses can be adapted by changing mold specifications (e.g., use of indentations), altering spring dimensions enables the modification of pocket spring mattresses, and polyurethane mattress elasticity can be adjusted by using different kinds of foam (e.g., different densities). A correlation will be established with general material properties (elasticity in particular), independent of the actual materials used.

Most mechanical properties can be described by standardized compression and tensile tests. Displacement-controlled benches measure force at a fixed interval, resulting in a force-displacement characteristic consisting of a loading and a relaxation phase, which can be recalculated to a stress-strain characteristic. Elasticity can be calculated as the ratio of stress to strain; the more force is needed to reach a certain impression, the firmer the mattress will be. In the case of a perfectly elastic material, elasticity will be constant. In the case of a viscoelastic material (e.g., polyurethane), elasticity is dependent on the velocity of deformation. Other mechanical tests (e.g., standard tensile tests) are also performed, but are not described here, as their output parameters are not used for mattress evaluation purposes; they are intended for computer modeling only, as illustrated in the previous chapter.

At present, several ISO 9002 standards of elasticity measurements are in use. The most important are described by the ISO 2439/B MOD 1 standard, including a German (LGA) (DIN 1991) and a French-Swedish (CTBA/Möbelfacta) (Möbelfacta 1990) variation. Both methods are briefly explained here; a detailed description can be found in the ISO documents.

For LGA-testing, the entire core of a mattress is positioned in a compression bench, while a metal sphere segment (diameter \( d = 355 \) m, sphere radius \( r = 800 \) m, total contact surface \( s = 1000 \text{ cm}^2 \)) applies pressure to discrete points \( p \), as illustrated in Figure 5.8 (left). A total force ranging from 0 N to 1000 N is applied with a constant bench velocity of 90 mm per minute, and mattress impression is measured at four load levels: 0, 50, 450, and 1000 N. The actual measurement is carried out after three identical prefatiguing load cycles; force-displacement characteristics (Figure 5.8 right) are registered and saved. In order to prevent airflow occlusion at the bottom plate of the test bench, holes with a diameter of 6 mm are foreseen at a distance of 20 mm from each other.
The hysteresis $H$ (in percentages) of the mattress core can be calculated as the factor $A_1/A_2 \times 100$, with $A_1$ the area between the load curve and the relief curve and $A_2$ the total area under the load curve. Further, the firmness of the mattress core is indicated by the factor $E/C$ (mm$^2$), with $E$ (N·mm) the work needed to compress the core up to a total force of 450 N, and $C$ (N/mm) the average differential firmness. $E$ can be derived by calculating the total area under the load curve up to 450 N, and $C$ by calculating the average slope of the tangent lines to the load curve at 210, 275, and 340 N. According to LGA standards, factors $E/C$ lower than 900 mm$^2$ indicate firm mattresses, factors $E/C$ between 900 mm$^2$ and 1800 mm$^2$ indicate mattresses with an average firmness, and factors $E/C$ higher than 1800 mm$^2$ indicate soft mattresses. Finally a dimensionless subjective firmness index $S$ can be derived from $E/C$, as described in the literature (DIN 1991); firm mattresses have $S$-values lower than 2.5 while soft mattresses have $S$-values higher than 3.5.

$$S = 5 \left(1 - \frac{E}{C} \left(\frac{100,000}{2.51} \right)^{(-59.2)}\right)$$

(5.1)

For CTBA testing, the mattress core needs acclimatization before testing: a minimal period of 24 hours at a temperature of 23°C (±2°C) and a relative humidity of 50% (±5%) is required. Further, the entire core of the mattress is positioned on a compression bench, while a metal cylinder (diameter $d = 100$ mm) applies pressure to discrete points $p$, as illustrated in Figure 5.9 (left). A total force ranging from 0 to 250 N is applied with a constant bench velocity of 100 mm per minute, and mattress impression is measured at four load levels: 4, 40, 200, and 250 N. After 100 prefatiguing cycles with a total load of 1200 N and 1 prefatiguing cycle with a load of 300 N, the actual measurement is carried out. Force-displacement characteristics (Figure 5.9 right) are registered and saved. To prevent airflow occlusion at the bottom plate of the test bench, holes with a diameter of 6 mm are placed at a distance of 20 mm from each other.
The firmness of the mattress is indicated by three factors: \( d_{\text{surface}} \), \( d_{\text{core}} \), and \( d_{\text{bottom}} \), representing the impression differences (in mm) between 4 and 40 N (surface), 4 and 200 N (core), and 200 and 250 N (bottom). As for LGA-testing, the hysteresis \( H \) (in percentages) can be calculated as the factor \( A_1/A_2 \times 100 \), with \( A_1 \) the area between the load curve and the relief curve (both limited to 250 N), and \( A_2 \) the total area under the load curve (limited to 250 N).

Both LGA and CTBA output parameters can be visualized by cartographies, indicating the output with a color value at all measurement points over the entire mattress surface. ISO lines, connecting points with equal parameter values, make it easy to trace or to control specific mattress characteristics (e.g., elasticity variations), as illustrated in Figure 5.10.

5.1.1.2 Output Data: Monitoring of the Spine during Recumbent Testing

At the first stage of the measurement process, optical tracking was conceived to evaluate lateral and supine positions, as described in Chapter 3. For a lateral sleep position,
markers glued to the skin covering the spinous processes are detected by a Qualisys MAC-Reflex® camera system (±0.12 mm). For supine sleep positions, a system with pins piercing through the mattress measures the spinous process positions. These positions are automatically digitized and transferred into a spreadsheet format for further analysis. The position and orientation of the vertebrae are estimated, and the shape of the spine is evaluated based on different parameters depending on the posture.

At the second stage of the measurement process, white-light raster line triangulation (WLRT) hardware and active contour software were successfully applied to the evaluation of the spine in three dimensions, as described in Chapter 3. Using triangulation algorithms, WLRT is able to quantify a back’s surface in three dimensions. Anatomical landmarks and the line through the spinous processes are then traced as a starting point for the reconstruction of the inner spine, in order to assess the shape of the vertebral column.

5.1.2 Data Processing

By registering input and output parameters thoroughly, a complete picture of a subject on a sleep system is obtained. Consequent result processing on a well-balanced measurement mix of persons and sleep systems will (1) allow prediction of the output behavior (the shape of the spine) as a function of the input (the combination subject-sleep system) and (2) yield a correlation between body dimensions, such as shoulder width and Quetelet index (Godeaux 1973), and corresponding appropriate mattress characteristics, generating an optimal output.

A typical output data set to be processed consists of a list of point coordinates sampling the spinal curvature in three dimensions. This type of data structure is continuously applied throughout the study, no matter which data acquisition method is used (e.g., optical tracking or WLRT) or which body position is measured (e.g., upright or recumbent).

Data processing generally consists of two stages. Initially the shape of the spine during bedrest is evaluated by calculating the deviation from its shape during upright standing. Thereupon, different sleep systems are evaluated by comparing the spinal deviations that are effected by each of them.

5.1.2.1 Shape of the Spine

The reference position practiced throughout this book gives the spinal column—more precisely in a midsagittal cross section—the same thoracic kyphosis and lumbar lordosis as in an upright position, yet slightly smoothened because, in a sleep position, the direction of the gravitation vector no longer coincides with the cranio-caudal direction of the body; a prolongation of the spine of 2% and a consequent smoothening (Krag et al. 1990)—as during weightlessness—is applied to the reference. The deviation from this reference shape is quantified by parameters P₁ to P₅ (P₁ to P₄ are obtained from the literature (Pheasant 1991); P₅ is defined below), producing a set that sufficiently characterizes the spine in a midsagittal cross section. Redundant parameters are removed at a later stage.
The first parameter (P₁ in Figure 5.11, ±1.21°) quantifies lordosis by measuring the angle between (1) the tangent to the spine in the geometric bending point b₁ at the transition from sacral kyphosis to lumbar lordosis and (2) the tangent to the spine in the geometric bending point b₂ at the transition from lumbar lordosis to thoracic kyphosis. A second parameter (P₃ in Figure 5.11, ±0.6 mm) also quantifies lordosis, by measuring the maximal distance between the lordotic spinal curvature and its least square line. Further, the characteristics of thoracic kyphosis (between b₂ and b₃) are quantified in a similar way (P₂ ±2.31°, and P₄ ±0.7 mm), where b₃ is located at the transition from the thoracic kyphosis to the cervical lordosis.

Finally, an overall evaluation is made by determining the mean-square perpendicular distance from the spinal curvature to its least square line (parameter P₅ ±0.3 mm), as illustrated in Figure 5.12. Distances D and the mean distance P₅ are calculated using 17 measurement points (the thoracic processi spinosi T1 to T12 and the lumbar processi spinosi L1 to L5). A cosine is introduced by a coordinate transformation, changing the reference coordinate system from a system relative to the person to an absolute reference system. Calculating the area between the spine and its least square line or using (engineering) parameters that are used to characterize the smoothness of a surface (Kruth 1993) might be other possibilities to describe the flattening of the spine. Taking into account the relative importance of P₅ (see Section 5.1.2.2.1), no further attempt is made to refine this factor.
In accordance with the definition of optimal spinal alignment, the frontal projection of the spinal column has to approximate the reference shape, being a straight line when normal healthy people are measured. The deviation from this line is quantified by three parameters (P₆ to P₈). The mean distance (P₆, ±0.8 mm) measured in a transversal direction from the measurement points to the least square line through these points is the first frontal parameter. The angle of the same least square line with respect to the reference coordinate system (P₇, ±0.67°) is the second parameter and is only relevant in the case of a lateral sleep position. Further, the spinal slope often shows a discontinuity around vertebra T11 at the transition from the flexible lumbar area to the more rigid thoracic area—especially in a lateral position—and measurement points are subdivided into two parts separated by this vertebra. For each part the least square line is calculated, and the angle between the two lines (P₈, ±1.14°) defines the third frontal parameter, as illustrated in Figure 5.13.

In addition to sagittal and frontal bending properties, three-dimensional torsion characteristics are relevant. To quantify this feature, osculating planes (o₁, o₂, and o₃) and normal vectors (\( \hat{\mathbf{n}}_1, \hat{\mathbf{n}}_2, \) and \( \hat{\mathbf{n}}_3 \)) on these planes are calculated in all three previously described bending points (b₁, b₂, and b₃). Lumbar torsion (P₉, ±1.56°) is defined as the angle between the normal lines in b₁ and b₂; thoracic torsion (P₁₀, ±3.14°) is defined as the angle between the normal lines in b₂ and b₃, as illustrated in Figure 5.14.
FIGURE 5.14 Three-dimensional torsion shape of the spine: parameter \( P_9 \).

TABLE 5.2 Parameters to Assess the Shape of the Spine

<table>
<thead>
<tr>
<th>Par.</th>
<th>Classification</th>
<th>Description</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_1 )</td>
<td>Sagittal</td>
<td>Lumbar lordosis angle</td>
<td>Lordosis</td>
</tr>
<tr>
<td>( P_2 )</td>
<td>bending</td>
<td>Maximal lumbar distance to least square line</td>
<td></td>
</tr>
<tr>
<td>( P_3 )</td>
<td>properties</td>
<td>Thoracic kyphosis angle</td>
<td>Kyphosis</td>
</tr>
<tr>
<td>( P_4 )</td>
<td></td>
<td>Maximal thoracic distance to least square line</td>
<td></td>
</tr>
<tr>
<td>( P_5 )</td>
<td></td>
<td>Mean square deviation of the spine to the sagittal projection of the least square line</td>
<td>Smoothness</td>
</tr>
<tr>
<td>( P_6 )</td>
<td>Frontal bending</td>
<td>Mean square deviation of the spine to the frontal projection of the least square line</td>
<td>Scoliosis</td>
</tr>
<tr>
<td>( P_7 )</td>
<td>properties</td>
<td>Mean deviation angle of the spine with respect to the reference coordinate system</td>
<td>Trunk tilt</td>
</tr>
<tr>
<td>( P_8 )</td>
<td></td>
<td>Angle between the thoracic and lumbar part of the spine</td>
<td>Buckling</td>
</tr>
<tr>
<td>( P_9 )</td>
<td>Torsion</td>
<td>Torsion angle of the lumbar spine</td>
<td>Torsion</td>
</tr>
<tr>
<td>( P_{10} )</td>
<td>properties</td>
<td>Torsion angle of the thoracic spine</td>
<td></td>
</tr>
</tbody>
</table>

Deviations from the reference position are calculated and normalized (by dividing it by the reference position value) for all 10 parameters in order to obtain homogeneous and dimensionless values that are combinable. Parameter descriptions are summarized in Table 5.2.

As mentioned before, measurements usually are performed at least three times to enhance the estimation of the measured spinal deformations. In this case, the subject has to be positioned in the same way for all exposures, adopting (1) an erect posture in the case of a supine sleep position and (2) the semi-Fowler’s position (bending hip and knee joints at 135° and 90°, respectively) in the case of a lateral position. This absolute
positioning is controlled by anatomical landmarks; the spina iliaca anterior superior, the acromion and the top of the head are located by palpation and positioned on a fixed distance in cranio-caudal direction from the mattress end.

After each measurement the test person takes a short pause and is correctly repositioned by relocating the anatomical landmarks. When measurements are performed at least three times, spinal alignment parameters are calculated as the mean value over all exposures.

5.1.2.2 Sleep System Evaluation

After calculating and normalizing the deviations from the reference position for each parameter, the deviations have to be combined in a weighted average (WA) to provide an overall estimation of the quality of spine support. A procedure comparable to neural networking (see Chapter 4) was used to set the weights of all relative deviations in an iterative way. The resulting algorithm rates the support qualities of a sleep system in the same way an experienced specialist would do.

**TABLE 5.3 Initial Weight Settings**

<table>
<thead>
<tr>
<th>Spine Parameter</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>5</td>
</tr>
<tr>
<td>P₂</td>
<td>10 hypo/15 hyper</td>
</tr>
<tr>
<td>P₃</td>
<td>1</td>
</tr>
<tr>
<td>P₄</td>
<td>2</td>
</tr>
<tr>
<td>P₅</td>
<td>1</td>
</tr>
<tr>
<td>P₆</td>
<td>10</td>
</tr>
<tr>
<td>P₇</td>
<td>5</td>
</tr>
<tr>
<td>P₈</td>
<td>2</td>
</tr>
<tr>
<td>P₉</td>
<td>10</td>
</tr>
<tr>
<td>P₁₀</td>
<td>2</td>
</tr>
</tbody>
</table>

In order to attain this objective, initial weight values (based on relevant expertise, including literature) are gradually refined in such a way that the system generates the same results compared to the judgment of three independent experts. This procedure is followed for a training group of 20 measured cases. In order to control the resulting refined parameters, system and expert results are compared for an independent measurement group of 10 cases.

5.1.2.2.1 Initial Setting

The higher the negative influence of a parameter deviation (e.g., scoliosis) on the overall support quality, the larger the corresponding weight factor should be. As for frontal
bending parameters, the mean absolute distance deviation (P₆) is more important than the described angles (P₇ and P₈). As for sagittal bending and torsion parameters, the thoracic region (P₃, P₄, and P₁₀) is much less important than the lumbar region (P₁, P₂, and P₉), where hyperlordosis has to be considered more negative than a hypolordosis. Further, mean absolute distance deviations are more important—and accurate—than angle deviations. This information provides the initial weight settings illustrated in Table 5.3. The higher the overall negative influence of the sleep system on the spine, the larger the weighted spinal deformations on it will be, and the higher the resulting number indicating the quality of the spinal alignment.

### 5.1.2.2.2 Final Setting

In order to achieve a correct sleep system comparison, the subject has to be repositioned in the same way for all analyzed sleep systems. This absolute position is controlled as described in the previous subsection; small posture differences, however, cannot be avoided and will propagate throughout the calculations, which is one of the three main difficulties concerning the initial weight setting:

**TABLE 5.4 Refined Weight Settings**

<table>
<thead>
<tr>
<th>Spine Parameter</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>P₁</td>
<td>0</td>
</tr>
<tr>
<td>P₂</td>
<td>2 hypo/5 hyper</td>
</tr>
<tr>
<td>P₃</td>
<td>0</td>
</tr>
<tr>
<td>P₄</td>
<td>1</td>
</tr>
<tr>
<td>P₅</td>
<td>1</td>
</tr>
<tr>
<td>P₆</td>
<td>10</td>
</tr>
<tr>
<td>P₇</td>
<td>2</td>
</tr>
<tr>
<td>P₈</td>
<td>5</td>
</tr>
<tr>
<td>P₉</td>
<td>5</td>
</tr>
<tr>
<td>P₁₀</td>
<td>2</td>
</tr>
</tbody>
</table>

1. Weight settings are subjective—an overall impression is given—rather than objective.
2. All parameters are judged separately while they are sometimes interdependent (e.g., P₁ and P₂).
3. Some parameters are more sensitive to repositioning errors, so their influence should be decreased in favor of more accurate parameters describing the same spine properties.

These problems are tackled by a consequent weight refinement based on a training set of 20 measured cases. All weights are optimized iteratively so that the resulting average rates the support qualities of a sleep system in the same way an experienced specialist would do. For example, a smaller weight factor was appointed to lumbar torsion, as this
factor is influenced by varying lateral body posture rather than by sleep system quality. The resulting weights (see Table 5.4) were successfully controlled by applying and checking them on a second measurement group ($n=10$).

### 5.1.3 Measurement Sequence

As discussed before, both “input” and “output” parameters are monitored to obtain a complete picture in the course of analyzing the vertebral column of a subject on a sleep system. Input parameters can be subdivided into two classes: anthropometrical characteristics and sleep system properties. Output parameters—affecting the position and orientation of the spine—are summarized in one single number (i.e., the weighted parameter average).

Each of the three stages (see Sections 5.1.3.1 to 5.1.3.3) in the measurement sequence aims to evaluate test persons on a group of sleep systems to (1) predict how a certain person $x$ will be supported by a sleep system $y$ and (2) correlate anthropometrical properties and optimal sleep system characteristics. Each stage compares sleep systems that only differ in a limited number of properties to facilitate the succession of measurements and to simplify the determination of less relevant parameters. A simple example with two test persons (T1, slim and T2, heavy) and two sleep systems (S1, firm and S2, soft), all characterized by only one parameter (body weight $T$ and mattress firmness $S$, respectively), is illustrated in Table 5.5.

The first stage in the measurement sequence should be simple (e.g., by including only a limited number of bed parameters) to provide simple, general guidelines. To keep a clear sight on the situation, complications (e.g., stiffness zones in the mattress) have to be added gradually throughout the different stages. The acquired knowledge at the end of each stage (e.g., a parametric correlation) enables the performance of more complex measurements at the next stage, with the ability to evaluate advanced types of sleep systems at the end of the sequence.

<table>
<thead>
<tr>
<th>Test Person</th>
<th>Sleep System</th>
<th>Resulting Parameter Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>S1</td>
<td>$R_1$</td>
</tr>
<tr>
<td>T1</td>
<td>S2</td>
<td>$R_2 (&lt;R_1)$</td>
</tr>
<tr>
<td>T2</td>
<td>S1</td>
<td>$R_3 (&lt;R_4)$</td>
</tr>
<tr>
<td>T2</td>
<td>S2</td>
<td>$R_4$</td>
</tr>
</tbody>
</table>

**Conclusions**

- Person $x$ (interpolated between 1 and 2) on system $y$ (idem) will yield an interpolated result $R$
- T1 is best with S2 and T2 is best with S1

$=>$ Positive correlation between body weight and mattress firmness

TABLE 5.5 Exemplary Measurement Set
While in the beginning only predetermined systems (e.g., with a fixed mattress stiffness) are used, flexible types (e.g., with the ability to adjust or optimize stiffness properties) are measured later. These have the advantage of measuring optimal settings, which yields a better correlation—if existing—between anthropometries and optimal bed characteristics, but have the disadvantage of always needing an expert eye during measuring.

Further, a certain level of standardization (e.g., bed base stiffness levels) will always be needed throughout the measurements, as a too individualized measurement set provides an unstructured database—which might be helpful for a limited number of individual cases only—instead of providing general guidelines or a clear insight into the underlying relationships.

5.1.3.1 Stage 1: Exploratory Measurements

5.1.3.1.1 Aim

The first measurement set is performed with the intention of verifying the influence of a firmer or softer mattress core on the shape and position of the vertebral column. Although it is commonly accepted that sleep systems with a homogeneous stiffness are able to offer only sufficient support to a limited

<table>
<thead>
<tr>
<th>Table 5.6 Sleep System Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Serial #</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Mattress 01</td>
</tr>
<tr>
<td>Mattress 02</td>
</tr>
<tr>
<td>Mattress 03</td>
</tr>
<tr>
<td>Mattress 04</td>
</tr>
<tr>
<td>Mattress 05</td>
</tr>
<tr>
<td>Mattress 06</td>
</tr>
<tr>
<td>Mattress 07</td>
</tr>
<tr>
<td>Mattress 08</td>
</tr>
<tr>
<td>Mattress 09</td>
</tr>
</tbody>
</table>
range of people, they still account for a big share of the market. This means that the guidelines extracted from these measurements—even though they are actually meant to provide the necessary information for further measurements—have a market value of their own. Measurements also verify whether commonly accepted assumptions are correct.

This set will further show which body characteristics are responsible when extreme deformations of the vertebral column occur, and which population classes will most likely benefit from a subdivision into stiffness zones (see Section 5.1.3.2).

### 5.1.3.1.2 Measurement Group

Measurements are performed for 30 people on 10 different mattresses for both supine and lateral sleep positions; a weighed parameter average (see Section 5.1.2.2.2) defines the best mattress for each person. The volunteers—16 male and 14 female, aged 25.1 yr (±5.5 yr)—do not suffer from spinal deformations, back pain, obesity, or muscle contractions. The shape of each volunteer’s spine is measured on 10 mattresses made of polyurethane, each with a different stiffness, as illustrated in Table 5.6. A rigid board is used for the bed base, keeping the corresponding parameters as simple as possible.

To provide simple guidelines based on a (multiple) linear correlation, it is important to choose a mattress mix that is equally distributed over the full scale of sleep systems. Consequently, a dense mix (at least 10 mattresses) is needed to cover the most used range with a sufficient accuracy, as illustrated in Figure 5.15. Further, the wide stiffness range will underline the relation—if existing—with anthropometrical parameters.

### 5.1.3.1.3 Protocol

First, anthropometrical parameters are acquired with a laser system (see Section 5.1.1.1.1) measuring body contours. The shape of the spine is then

**FIGURE 5.15** Mattress and base characteristics.
measured in an upright position and on 10 mattresses with a three-dimensional tracking system (see Section 5.1.1.2) for both a lateral and a supine sleep position. To reposition the test persons in the same way on every sleep system, the person is inquired to adopt (1) an erect posture in the case of a supine sleep position and (2) the semi-Fowler’s position in the case of a lateral position, which is controlled by anatomical landmark positioning. Measurements are performed five times on every sleep system to enhance the estimation of the measured spinal deformations. A more detailed description of these measurements is provided by Notelaers and Oris (1997).

5.1.3.2 Stage 2: Influence of Local Diversification

5.1.3.2.1 Aim

The second set of measurements studies the response of the vertebral column of different population groups to different kinds of mattresses and bed bases, especially when sleep systems are subdivided into several zones in the cranio-caudal direction, each having different local material properties (e.g., a softer shoulder zone or a firmer pelvic zone). As a combination of mattress and bed base diversification would imply a too large increase of bed parameters at this stage, their effect is measured separately.

Although it is commonly accepted that incorrect local interventions might be harmful in some cases (e.g., setting a softer pelvic zone), the influence of this kind of zones is observed to statistically verify whether commonly accepted assumptions are correct.

5.1.3.2.2 Measurement Group

At first, mattress zones are evaluated: 40 people are measured in a lateral sleep position, and a weighed parameter average (see Section 5.1.2.2.2) defines the best mattress. The volunteers—19 male and 21 female, aged 26.1 yr (±6.3 yr)—are not suffering from spinal deformations, back pain, obesity, or muscle contractions. The shape of each volunteer’s spine is captured on five mattresses made of polyurethane blocks (i.e., one block for the head, one for the shoulders, one for the waist, one for the pelvis, and one for the legs). Each block has different properties (see Table 5.7). Only the

<table>
<thead>
<tr>
<th>TABLE 5.7 Sleep System Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CTBA Core (mm)</strong></td>
</tr>
<tr>
<td>Serial #</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Mattress 01 5514/01</td>
</tr>
<tr>
<td>Mattress 02 5514/02</td>
</tr>
<tr>
<td>Mattress 03 5514/03</td>
</tr>
<tr>
<td>Mattress 04 5514/04</td>
</tr>
<tr>
<td>Mattress 05 5514/05</td>
</tr>
</tbody>
</table>

*Note: Characteristics of mattress+reference base.*
most important stiffness characterization—the CTBA core value—is represented in the table. In order not to blur the potential relationship with mattress parameters, a rigid board is used for the bed base, keeping the corresponding parameters as simple as possible. Head and feet blocks have a constant CTBA core value of 63.

At this second stage, measurements still aim at establishing a correlation with general material properties (elasticity in particular), as it is possible to obtain the required elasticity characteristics with any material by producing or adjusting it correctly (see Section 2.1). Therefore, only mattress cores are evaluated. Commercial sleep systems (e.g., including a top layer) are only measured at the third stage of the measurement sequence.

Material differences are clearly visible in Figure 5.16 and Figure 5.17. The CTBA core stiffness is measured at a discrete number of points and interpolated over the entire bed surface. All mattresses are characterized on a rigid base for reference.

Next, bed base zones are evaluated. The same 40 people are measured in a lateral sleep position. The shape of each person’s spine is captured on three

![Figure 5.16](image)

**FIGURE 5.16** $d_{core}$ cartography for mattress with soft pelvic zone.
different bed bases, each with different stiffness zones, as illustrated in Table 5.8. Different stiffness properties are obtained by changing the suspension of the slats. To obtain the same vertical displacement at each point of an individual slat, all bases consist of aluminum slats that are suspended (in the mediolateral direction) on variable metal springs. A polyurethane mattress without stiffness zones (sample number 5514/01) is used to keep the corresponding parameters as simple as possible, with the intention not to blur a potential relationship with bed base parameters.

Material differences are illustrated on the Figure 5.18 and Figure 5.19. CTBA bed base core stiffness is characterized—in combination with a reference mattress—by measuring it at a discrete number of points and by interpolating these values over the entire surface. Base differences, however, are small compared to mattress variation; as an example, the difference between a base with a homogeneous stiffness (Figure 5.18) and a base with a softer shoulder zone (Figure 5.19) is only marginal.

Indeed, bed base zone differences are actually smoothed by the mattress; as compared to a rigid base, a flexible bed base—with or without stiffness zones—decreases the overall stiffness almost equally at all locations. This is illustrated by comparing Figure 5.10 (a homogeneous mattress without

---

**TABLE 5.8 Sleep System Characteristics**

<table>
<thead>
<tr>
<th>Serial #</th>
<th>Shoulder</th>
<th>Waist</th>
<th>Pelvis</th>
<th>Subj. Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bed base 01</td>
<td>02354/01</td>
<td>91</td>
<td>92</td>
<td>93</td>
</tr>
<tr>
<td>Bed base 02</td>
<td>02354/02</td>
<td>100</td>
<td>95</td>
<td>92</td>
</tr>
<tr>
<td>Bed base 03</td>
<td>02354/03</td>
<td>92</td>
<td>90</td>
<td>85</td>
</tr>
</tbody>
</table>

*Note:* Characteristics of mattress+reference mattress.
5.1.3.2.3 Protocol

For each of the 40 test persons, anthropometrical parameters are acquired with a digital sliding caliper mounted on a similar vertical slide (see Section 5.1.1.1.1). Reference measurements of thoracic kyphosis and lumbar lordosis in an upright standing position are performed with the same white-light raster line triangulation system used for prone postures and, therefore, are included as a reference run at the beginning of each measurement sequence. The shape of the spine is then measured for a lateral sleep...
position on five different mattresses (with a reference base) and three different bed bases (with a reference mattress). To reposition the test persons in the same way on every sleep system, the person is asked to adopt the semi-Fowler’s position, which is controlled by anatomical landmark positioning. Measurements are performed five times on every sleep system to enhance the estimation of the measured spinal deformations. A more detailed description of these measurements is available (Motmans 2000).

5.1.3.3 Stage 3: Influence of Local Modifiability

5.1.3.3.1 Aim

At the first two stages, only predetermined sleep systems were evaluated by selecting the one with the best support qualities out of a limited range of sleep systems. At this third (and last) stage, more flexible types—with the ability to adjust or optimize stiffness properties—are measured. On one hand, these flexible types have the advantage that optimal settings can be applied and measured for each individual, which yields a better correlation—if existing—between anthropometries and optimal bed characteristics. On the other hand, they have the disadvantage that an expert is always needed during measuring. Also, the main commercial advantage of this kind of adjustable mattress—being the modifiability of a standard product—stands or falls with the quality of the expert guidelines provided to obtain the economically best-suited tuning per customer profile.

While previous measurements aimed at a zone definition—whether mattress zones are needed, and if so, which zones are required for different population groups—this stage aims at zone quantification. It will define which stiffness values have to be applied to each zone, depending on anthropometrical properties, and verify whether these values are consistent with earlier measurements.

5.1.3.3.2 Measurement Group

At first, mattress zones are evaluated: 40 people are measured in a lateral sleep position, and a weighed parameter average (see Section 5.1.2.2.2) defines the best mattress setting for each zone. The volunteers—20 male and 20 female, aged 28 yr (±6.3 yr)—do not suffer from spinal deformations, back pain, obesity, or muscle contractions.

To provide a (multiple) linear correlation between anthropometrical characteristics and stiffness values, at least two different stiffness levels should be applied to every adjustable zone (shoulder, waist, and pelvic). As combining these levels would result in an insurmountable increase in building and measuring time when using polyurethane blocks, a mattress with three independently tunable air chambers is used, which simulates the desired mattress mix; three independently operated manometers indicate the pressure levels inside the air chambers on a scale from 0 to 10. There are no air chambers in the head and leg zones, which have, as a result, constant properties. The system is also commercially available as ADS® (Air-Dämpfungs-System) by Schlaraffia®, for which the term “air chamber system” will be used.
### TABLE 5.9 Weighted Sum at Extreme Air Chamber Pressure Levels

<table>
<thead>
<tr>
<th></th>
<th>Bultex</th>
<th>Foam</th>
<th>Latex</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject A</td>
<td>199</td>
<td>257</td>
<td>256</td>
</tr>
<tr>
<td>Subject B</td>
<td>227</td>
<td>195</td>
<td>181</td>
</tr>
<tr>
<td>Subject C</td>
<td>209</td>
<td>181</td>
<td>273</td>
</tr>
<tr>
<td>Total</td>
<td>635</td>
<td>633</td>
<td>710</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>CTBA Core (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Shoulder</td>
</tr>
<tr>
<td>Mattress 01</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 02</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 03</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 04</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 05</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 06</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 07</td>
<td>83.5</td>
</tr>
<tr>
<td>Mattress 08</td>
<td>80.2</td>
</tr>
<tr>
<td>Mattress 09</td>
<td>80.2</td>
</tr>
<tr>
<td>Mattress 10</td>
<td>80.2</td>
</tr>
<tr>
<td>Mattress 11</td>
<td>80.2</td>
</tr>
<tr>
<td>Mattress 12</td>
<td>80.2</td>
</tr>
<tr>
<td>Mattress 13</td>
<td>Optimal tuning (user)</td>
</tr>
<tr>
<td>Mattress 14</td>
<td>Optimal tuning (expert)</td>
</tr>
</tbody>
</table>

*Note:* Characteristics of air chamber mattress + reference base.

The resulting mattress stiffness, however, is highly dependent on the surrounding material. Consequently, three different types of air chamber systems are evaluated in an exploratory phase: air chambers surrounded by Bultex®, by polyurethane foam, and by latex. Table 5.9 shows the weighed parameter average (see Section 5.1.2.2) as a measure of the adjustability of the three air chamber systems. The latex mattress was most adjustable and had the highest influence on the shape of the spine of the three measured
subjects, as it is able to deform locally. This behavior further decreases the resistance of the surrounding material at the considered indentation point, which will result in lower CTBA core values, as illustrated in Table 5.10. The combination of air chambers with latex, therefore, is suited to simulate a wide range of mattress types and will be used for all subsequent measurements.

Factory measurements demonstrate that pressure levels—in combination with a latex mattress—correlate well with standard mattress characteristics, as illustrated by Figure 5.20 and Equation 5.4 (with $P$ the manometer pressure level and $C$ the CTBA core value).

![FIGURE 5.20 CTBA core value as a function of pressure level.](image)

$$C=84.26+(-1.97)\cdot P$$

The main advantage of this correlation is that pressure levels can be recalculated to CTBA core values and vice versa, so that both units can be used interchangeably.

As measurements at this stage tend to be more individualized, a certain level of standardization is needed to provide general guidelines and a clear insight in the underlying relationships. Therefore, 12 standard levels are measured before optimizing the settings individually. Further, a rigid board is used for the bed base, keeping the corresponding parameters as simple as possible, in order not to blur the potential relationship with mattress parameters. Table 5.10 illustrates the mattress characteristics that are simulated by the air chamber system.

After measuring standard levels (mattresses 1 to 12 in Table 5.10), the person being tested gives his/her subjective impression of how the system should be adjusted until it provides a comfortable feeling (mattress 13 in Table 5.10). During the last measurement, the measuring expert adapts the system until the spinal column of the test person is lying in an optimal position (mattress 14 in Table 5.10).

Because pressure levels can be adjusted while the subject remains in a lying position, no subject repositioning is needed between exposures, which improves measurement repeatability.

Second, bed bases are evaluated. The same group of subjects is measured in a lateral sleep position, and a weighed parameter average (see Section 5.1.2.2) defines the best mattress adjustment for each zone. It is important to measure (1) how a base influences the spine when the air chamber system is set in accordance with the values generated by the previous measurement sequence (mattresses 13 and 14) and (2) how the air chamber system should be modified to obtain the correct position of the spine for each base. This
results in an indication of (1) which bases are suited to be combined with mattresses with zones and (2) which adjustment is optimal for each population group. Five different bed bases—all commercially available at the time of writing—were evaluated and listed in Table 5.11. On a relative scale, the local flexibility of the five bases increases with the base number.

**TABLE 5.11 Bed Base Types**

<table>
<thead>
<tr>
<th>Bed Base</th>
<th>Producer</th>
<th>Type</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Reference Base</td>
<td>Wood</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Rocado</td>
<td>Karat KF</td>
<td>Wood</td>
</tr>
<tr>
<td>2</td>
<td>Schlaraffia</td>
<td>Comfort-Matic</td>
<td>Wood</td>
</tr>
<tr>
<td>3</td>
<td>Schlaraffia</td>
<td>Wave</td>
<td>Plastic</td>
</tr>
<tr>
<td>4</td>
<td>Schlaraffia</td>
<td>Lexor I</td>
<td>Plastic</td>
</tr>
<tr>
<td>5</td>
<td>Lattoflex</td>
<td>Winx 200</td>
<td>Plastic</td>
</tr>
</tbody>
</table>

**5.1.3.3.3 Protocol**

For each of the 40 test persons, anthropometrical parameters are acquired with a digital sliding caliper mounted on a vertical slide (see Section 5.1.1.1.1). Reference measurements of thoracic kyphosis and lumbar lordosis in an upright standing position are performed with the same white-light raster line triangulation system used for lying postures.

For the first measurement sequence, the shape of the spine in a lateral sleep position is measured on 14 different mattresses (see Section 5.1.3.3.2). As mentioned before, the first 12 measurements concern standard levels, while the last two affect an individual level optimization, as advised by the subject and by the measuring expert. All measurements are performed with the test person lying on his or her side, in a semi-Fowler’s position (bending hip and knee joints 135° and 90°, respectively). Further, the test person was positioned in such a way that the sacrum point was located in the center of the mattress.

For the second measurement sequence, spine deformations are evaluated when the air chamber mattress is modified in accordance with the previously defined optimal air chamber pressure values (mattresses 13 and 14, as advised by the customer/expert for a reference base) in combination with each of the five different bed bases. Further, spine deformations are evaluated again when settings are optimized in accordance with both customer (customer+) and expert (expert+) opinion for every bed base. This results in a measurement sequence consisting of four measurements for every base, as illustrated (for one base) in Table 5.12.
5.2 Results and Discussion

The first section of this chapter discussed the methodology that was used to gain a progressively clear insight into the impact of bed design on spine support. The second section of this chapter describes the actual measurement results and discusses how they contribute to the determination process of the optimal sleep system for each individual.

TABLE 5.12 Exemplary Measurement Sheet
(indicating pressure levels)

<table>
<thead>
<tr>
<th>Latex+Air Chambers Upright Position Reference</th>
<th>Person: X Code: SCHL4495</th>
<th>Date: 04/2001</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base 0: Optimal Settings without Base</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nr</td>
<td>Code</td>
<td>Shoulder</td>
</tr>
<tr>
<td>M13</td>
<td>SCHL4472</td>
<td>Customer</td>
</tr>
<tr>
<td>M14</td>
<td>SCHL4473</td>
<td>Expert</td>
</tr>
<tr>
<td>Base 1: Karat KF (Rocado)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nr</td>
<td>Code</td>
<td>Shoulder</td>
</tr>
<tr>
<td>B 01</td>
<td>SCHL4474</td>
<td>Customer</td>
</tr>
<tr>
<td>B 02</td>
<td>SCHL4475</td>
<td>Customer+</td>
</tr>
<tr>
<td>B 03</td>
<td>SCHL4476</td>
<td>Expert user</td>
</tr>
<tr>
<td>B 04</td>
<td>SCHL4477</td>
<td>Expert +</td>
</tr>
</tbody>
</table>

5.2.1 Stage 1: Exploratory Measurements

The first measurement set is performed with the intention of verifying the influence of a firmer or softer mattress core on the shape and position of the vertebral column. Based on the measurements of 30 people on 10 different mattresses, a correlation is established between anthropometrical characteristics and the mattress with the best support qualities, as defined by a weighted sum of parameters (see Section 5.1.2.2.2).

The coordinates of the spine and the error on these coordinates are calculated for each measurement of a subject on a mattress and for each sleep position. The resulting shape of the spine is then compared to the shape of the spine in a reference position. Both a midsagittal and a frontal cross section of the spine are considered, as discussed before (see Section 5.1.1.1.1).

5.2.1.1 Lateral Sleep Position

In the first step, the best mattress (out of 10) is defined for each of the 30 subjects, as illustrated in Figure 5.21. It is, however, not always possible to define the best mattress with a satisfactory confidence level, due to the propagation of measurement errors.
through the selection algorithm and to the relatively small differences between some of the evaluated mattresses. The overall propagation effect is quantified by calculating the error on the measured deformation of the vertebral column (WA, see Section 5.1.2.2) for each of the 30 persons on each of the 10 mattresses. Based on these errors, the confidence values of the selection of the best mattress can be defined for each person (Notelaers and Oris 1997). For 24 out of 30 subjects a confidence level of 95% is obtained when selecting the best mattress (out of ten). For the remaining six subjects, the best mattress could not be selected with this confidence level.

**FIGURE 5.21** Best mattress selection for 30 subjects.

**FIGURE 5.22** Exemplary correlation between anthropometrical characteristics and properties of best fitting mattress.

In the second step, a correlation—based on these optimal combinations—is traced between simple anthropometrical characteristics and mechanical properties of the best
corresponding mattress. In the case of a lateral sleep position, a highly significant correlation is established (e.g., between the weight/length\(^2\) factor of a subject and the CTBA core value of the best fitting mattress), as illustrated in Figure 5.22.

Table 5.13 summarizes the most significant results for a lateral sleep position. For each type of mattress characteristic, the correlation factor \(r^2\) and the significance level \(p\) are defined, both of which are dimensionless values. As CTBA surface values best describe the material behavior of a mattress when loaded by a subject lying on it, the most importance should be attributed to the corresponding correlation values. Only combinations with a confidence level of at least 95% are included in the calculations.

**TABLE 5.13 Correlation for a Lateral Sleep Position**

<table>
<thead>
<tr>
<th>Anthropometrical Characteristic</th>
<th>LGA (r^2) (p)</th>
<th>CTBA Surface (r^2) (p)</th>
<th>CTBA Core (r^2) (p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight/length(^2)</td>
<td>0.91 0.001</td>
<td>0.92 0.001</td>
<td>0.93 0.001</td>
</tr>
<tr>
<td>Upper trunk mass/upper trunk height</td>
<td>0.84 0.003</td>
<td>0.81 0.005</td>
<td>0.82 0.005</td>
</tr>
<tr>
<td>Trunk mass/trunk height</td>
<td>0.93 0.001</td>
<td>0.93 0.001</td>
<td>0.93 0.001</td>
</tr>
<tr>
<td>Upper trunk mass/upper trunk height(^2)</td>
<td>0.81 0.006</td>
<td>0.80 0.006</td>
<td>0.80 0.006</td>
</tr>
<tr>
<td>Upper trunk mass/upper trunk area</td>
<td>0.84 0.004</td>
<td>0.83 0.004</td>
<td>0.83 0.004</td>
</tr>
</tbody>
</table>

Based on these data, a multiple correlation is established between the five most significant anthropometrical parameters and the corresponding best fitting mattress properties.

### 5.2.1.2 Supine Sleep Position

In case of a supine sleep position, the best mattress (out of 10) is defined for each of the 30 subjects. For the larger part of the test group—22 out of 30 subjects—the best mattress can be selected with a confidence level of 95%. No significant correlation, however, could be established between simple anthropometrical characteristics and the mechanical properties of the best corresponding mattress. Nevertheless, a clear relation between advanced anthropometrical parameters (see Section 5.1.1.1.1) and the best mattress (out of 10) is identified, as illustrated in Table 5.14. Only combinations with a confidence level of at least 95% are included in the calculations.

Based on these data, a multiple correlation is established between the five most significant anthropometrical parameters and the corresponding best fitting mattress properties. This multiple correlation can be established for each type of mattress characterization (e.g., LGA or CTBA core), and is discussed in detail in the third measurement stage (see Section 5.2.3), as it will be more refined by then.
### TABLE 5.14 Correlation for a Supine Sleep Position

<table>
<thead>
<tr>
<th>Anthropometrical Characteristic</th>
<th>LGA</th>
<th></th>
<th>CTBA Surf.</th>
<th></th>
<th>CTBA Core</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r^2$</td>
<td>$p$</td>
<td>$r^2$</td>
<td>$p$</td>
<td>$r^2$</td>
<td>$p$</td>
</tr>
<tr>
<td>Upper trunk height</td>
<td>0.54</td>
<td>0.037</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Waist width/length</td>
<td>–</td>
<td>–</td>
<td>0.53</td>
<td>0.041</td>
<td>0.46</td>
<td>0.060</td>
</tr>
<tr>
<td>Waist width/length$^2$</td>
<td>–</td>
<td>–</td>
<td>0.68</td>
<td>0.011</td>
<td>0.59</td>
<td>0.026</td>
</tr>
<tr>
<td>Waist width/shoulder width</td>
<td>0.50</td>
<td>0.049</td>
<td>0.57</td>
<td>0.029</td>
<td>0.57</td>
<td>0.029</td>
</tr>
<tr>
<td>Lower trunk mass/lower trunk area</td>
<td>0.49</td>
<td>0.054</td>
<td>0.65</td>
<td>0.016</td>
<td>0.60</td>
<td>0.022</td>
</tr>
<tr>
<td>Trunk mass/trunk area</td>
<td></td>
<td></td>
<td>0.51</td>
<td>0.047</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Upper trunk conicity</td>
<td>0.55</td>
<td>0.340</td>
<td>–</td>
<td>–</td>
<td>0.45</td>
<td>0.067</td>
</tr>
<tr>
<td>Lower trunk mass/lower trunk area × trunk area</td>
<td>0.48</td>
<td>0.055</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

### 5.2.1.3 Discussion

An important accomplishment of this part of the study is the definition of adequate parameters to characterize an individual, to typify a sleep system, and to evaluate the resulting shape of the person’s spine while lying on this system. This modus operandi enables the extraction of conclusions from measurements.

For most subjects ($n=24$) the best mattress properties for a lateral sleep position were firmer than the optimal characteristics for a supine sleep position. An overall weighted average of mattress characteristics should be made based on the sleep positions of a particular subject during the night, if identified. Subjects were also asked to rate the mattresses subjectively, which pointed out that most people preferred to sleep on the mattress selected by the algorithm (50%) or on a firmer mattress (40%).

Furthermore, a notable inclination between the (flexible) lumbar region and the (rigid) thoracic region of the vertebral column was observed at T9–T11 (see Section 1.1.1.1 for the anatomy of the spine) for all measured subjects, especially on firmer mattresses. Therefore, one can hypothesize that the shoulder zone generally must be soft to prevent scoliosis in a lateral position. The hip zone of the mattress must be stiffened to prevent the pelvis from canting forward in a supine position and from tilting in a lateral sleep position.

The most significant outcome, however, is the difference between male and female subjects: parameters concerning the shoulder area (shoulder width/length, thorax width, upper trunk mass, etc.) are most relevant for male subjects, while parameters concerning the pelvic area (waist width/ pelvic width, lower trunk mass, etc.) are most relevant for female subjects. Also, correlations and significance levels are better when creating these subgroups, which is a strong indication that different anthropometrical characteristics...
should be considered for male and female subjects; consequently, all future measurements will incorporate this subdivision.

Male subjects with an athletic body build (large shoulder or thorax width) and female subjects with a pronounced body contour (small waist width with respect to pelvic width) are not sufficiently supported by sleep systems with a homogeneous stiffness, as large spinal deformations occur on these systems. These population groups will most likely benefit from a subdivision of the sleep system into different stiffness zones, as will be illustrated by the second measurement cycle.

Finally, mattresses are evaluated without a support structure at this stage, so results do not indicate quantitatively the perfect sleep system—including both mattress and support structure—for each individual. The results rather give a qualitative suggestion (1) of which population groups need firmer or softer mattresses (e.g., firmer mattress for heavier people), and (2) in which regions mattress stiffness should be adjusted, if possible (e.g., softer shoulder zone for males with an athletic body build).

These results partially correspond with findings by Hoogmartens (1984), who states in a very concise article that composed polyurethane layers are able to obtain optimal support for any type of subject. Furthermore, these results indicate that an extra-firm mattress—which is commonly believed to be beneficial for low back pain—is, in fact, not the best choice for the majority of the measured people. These results (dating back to 1997) were recently confirmed by Kovacs et al. (2003), who assessed the effect of different firmnesses of mattresses on the clinical course of patients with chronic nonspecific low back pain. Lahm and Iaizzo (2002) found that the spine was in much better alignment at midrange and higher mattress inflation pressures, but they did not refer to an absolute ISO scale for firmness, so results are difficult to compare. Unfortunately, these are—to the knowledge of the authors—the only articles in this specific research field, which prohibits additional comparative evaluations.

5.2.2 Stage 2: Influence of Local Diversification

The aim of the second set of measurements is to study the response of the vertebral column of different population groups to different kinds of mattresses and bed bases, especially when sleep systems are subdivided into several zones in the cranio-caudal direction, each having different local material properties (e.g., a softer shoulder zone or a firmer pelvic zone). As mentioned before, the difference between male and female subjects requires a subdivision into two test groups, which is possible as the entire test group \( n=40 \) is large enough to reach significant conclusions for each subgroup.

However, it will be difficult to determine a straightforward linear correlation between the anthropometrical characteristics and mechanical properties of the best corresponding sleep system, as only two different stiffness levels are defined for each zone (e.g., a firm and a medium-firm waist zone). As figures indicating the slope of the regression would be based on just two discrete Y-values, a straightforward linear correlation—and realistic slope figures—will be defined only at the third measurement stage, when a considerable number of (gradually increasing) stiffness levels are measured for each zone.

As it makes no sense to determine a correlation between anthropometrical characteristics and zone stiffness properties, a correlation is calculated between anthropometrical and the degree of spinal deformations for each of the zones.
This correlation does not quantify the magnitude of optimal zone characteristics, but it indicates which type of body build requires which type of zone subdivision.

### 5.2.2.1 Mattress Stiffness Zones

Correlations and significance levels are lower compared to the first measurement sequence, because more bed parameters—and uncertainties—are involved. Creating subgroups improves these correlations, as different anthropometrical characteristics should be considered for male and female subjects.

#### Table 5.15 Correlation for Male Subjects—Mattress Stiffness Zones

<table>
<thead>
<tr>
<th>Mattress Type</th>
<th>Anthropometrical Characteristic</th>
<th>CTBA Core</th>
<th>( r^2 )</th>
<th>Intercept</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous stiffness</td>
<td>Thorax width/length</td>
<td></td>
<td>0.82</td>
<td>-104.99a</td>
<td>797a</td>
</tr>
<tr>
<td></td>
<td>Thorax width/length(^2)</td>
<td></td>
<td>0.75</td>
<td>-79a</td>
<td>1174a</td>
</tr>
<tr>
<td></td>
<td>Trunk mass/length(^2)</td>
<td></td>
<td>0.65</td>
<td>-38a</td>
<td>6.4a</td>
</tr>
<tr>
<td></td>
<td>Body weight/length(^2)</td>
<td></td>
<td>0.60</td>
<td>-37a</td>
<td>3a</td>
</tr>
<tr>
<td></td>
<td>Thorax width</td>
<td></td>
<td>0.60</td>
<td>-92a</td>
<td>402a</td>
</tr>
<tr>
<td>Soft shoulder</td>
<td>Body weight</td>
<td></td>
<td>0.84</td>
<td>232a</td>
<td>-2.4a</td>
</tr>
<tr>
<td></td>
<td>Trunk mass</td>
<td></td>
<td>0.84</td>
<td>232a</td>
<td>-4.7a</td>
</tr>
<tr>
<td></td>
<td>Waist width/body weight</td>
<td></td>
<td>0.84</td>
<td>-145a</td>
<td>52480a</td>
</tr>
<tr>
<td></td>
<td>Shoulder width</td>
<td></td>
<td>0.80</td>
<td>640a</td>
<td>-1391a</td>
</tr>
<tr>
<td>Firm pelvis</td>
<td>Pelvic width/length</td>
<td></td>
<td>0.72</td>
<td>-166a</td>
<td>1210a</td>
</tr>
<tr>
<td></td>
<td>Lower trunk mass/length(^2)</td>
<td></td>
<td>0.70</td>
<td>-62</td>
<td>11.5a</td>
</tr>
<tr>
<td>Soft pelvis</td>
<td>Pelvic width/shoulder width</td>
<td></td>
<td>0.70</td>
<td>-168</td>
<td>300a</td>
</tr>
</tbody>
</table>

\( a p < 0.05. \)

For male subjects, parameters concerning the shoulder area are most relevant: the larger the width of the thorax, especially with respect to the (squared) body length, the larger the relative deformations of the spinal column on a mattress without stiffness zones. A soft shoulder zone will considerably improve support, and it is mandatory in the case of subjects with an athletic body build. A firmer pelvic zone is less important, but still advisable.

Table 5.15 shows the most relevant correlation between anthropometrical properties and the degree of spinal deformations for each of the zones. Although slope values...
should be considered with caution, some high values clearly indicate the adverse influence of some anthropometrical characteristics on the resulting shape of the spine.

For female subjects, parameters concerning the pelvic area are most relevant: the smaller the width of the waist, especially with respect to shoulder and pelvic width, the larger the relative deformations of the spinal column on a mattress without stiffness zones. A firm pelvic zone will considerably improve support, and it is mandatory in the case of subjects with pronounced body contours. A firmer waist zone is advisable; a soft shoulder zone is less important.

Further, a soft pelvic zone has disadvantageous consequences on the shape of the spine, as a large part of the body weight has to be supported in this region. The commonly accepted proposition—that a soft pelvic zone has a negative effect—therefore is verified.

Table 5.16 shows the most relevant correlation between anthropometrical properties and the gravity of spinal deformations for each of the zones. Although slope values should be considered with caution, some high values clearly indicate the adverse influence of some anthropometrical characteristics on the resulting shape of the spine, as was the case for male subjects.

### TABLE 5.16 Correlation for Female Subjects—Mattress Stiffness Zones

<table>
<thead>
<tr>
<th>Mattress Type</th>
<th>Anthropometrical Characteristic</th>
<th>( r^2 )</th>
<th>Intercept</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous</td>
<td>Lower trunk mass/lower trunk area</td>
<td>0.86</td>
<td>115(^a)</td>
<td>−0.11(^a)</td>
</tr>
<tr>
<td>stiff</td>
<td>Waist width</td>
<td>0.76</td>
<td>−32.8</td>
<td>496.9(^a)</td>
</tr>
<tr>
<td>Soft shoulder</td>
<td>Lower trunk mass</td>
<td>0.81</td>
<td>94.15(^a)</td>
<td>−2.58(^a)</td>
</tr>
<tr>
<td></td>
<td>Body weight</td>
<td>0.73</td>
<td>90.99(^a)</td>
<td>−0.98(^a)</td>
</tr>
<tr>
<td></td>
<td>Trunk mass</td>
<td>0.73</td>
<td>50.21(^a)</td>
<td>−120(^a)</td>
</tr>
<tr>
<td></td>
<td>Waist width</td>
<td>0.67</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Shoulder width</td>
<td>0.65</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Firm waist</td>
<td>Upper trunk mass/upper trunk area</td>
<td>0.69</td>
<td>152.34(^a)</td>
<td>−1.64(^a)</td>
</tr>
<tr>
<td></td>
<td>Lower trunk mass/lower trunk area</td>
<td>0.60</td>
<td>105.92(^a)</td>
<td>−0.1(^a)</td>
</tr>
<tr>
<td>Firm pelvis</td>
<td>Pelvic width/length</td>
<td>0.73</td>
<td>334752(^a)</td>
<td>−1714(^a)</td>
</tr>
<tr>
<td></td>
<td>Waist width/pelvic width</td>
<td>0.66</td>
<td>−219.01(^a)</td>
<td>323.5(^a)</td>
</tr>
<tr>
<td></td>
<td>Pelvic width</td>
<td>0.54</td>
<td>185.87(^a)</td>
<td>−491(^a)</td>
</tr>
</tbody>
</table>

\(^a\) \( p<0.05 \).

Based on these data, a multiple correlation is established between the five most significant anthropometrical parameters and the corresponding best fitting mattress zones.
for both male and female subjects. This multiple correlation is discussed in detail at the third measurement stage, as it will be more refined by then. Further, this correlation does not quantify the magnitude of optimal zone characteristics yet, but it indicates which type of body build requires which type of zone subdivision.

### 5.2.2.2 Base Stiffness Zones

As was the case for mattress stiffness zones, it is difficult to determine a straightforward linear correlation between anthropometrical characteristics and mechanical properties of the best corresponding base properties, as only two different stiffness levels are defined for each zone. Table 5.17 shows the most relevant correlation between anthropometrical properties and the gravity of spinal deformations for each of the zones. Yet again, high slope values clearly indicate the adverse influence of some anthropometrical characteristics on the resulting shape of the spine.

Conclusions are identical to those made for mattress zones, but correlations and significance levels are much lower, as stiffness variations are much smaller (see Section 5.1.3.2.2). For male subjects, a soft shoulder zone will improve support; for female subjects a firmer pelvic zone will achieve the same objective, as illustrated in Table 5.18.

As was the case for mattress zones, a multiple correlation is established between the five most significant anthropometrical parameters and the corresponding best fitting base zones for both male and female subjects. This multiple correlation is discussed in detail at the third measurement stage, as it will be more refined by then. This correlation does not quantify the

<table>
<thead>
<tr>
<th>Bed Base Type</th>
<th>Anthropometrical Characteristic</th>
<th>CTBA Core</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous</td>
<td>Upper trunk mass/upper trunk area</td>
<td>0.67</td>
<td>–22.2</td>
</tr>
<tr>
<td></td>
<td>Lower trunk area</td>
<td>0.73</td>
<td>–149.73&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Soft shoulder</td>
<td>Waist width/body weight</td>
<td>0.87</td>
<td>–54</td>
</tr>
<tr>
<td></td>
<td>Shoulder width</td>
<td>0.86</td>
<td>357&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Body weight</td>
<td>0.65</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Trunk weight</td>
<td>0.65</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Lower trunk mass/upper trunk mass</td>
<td>0.76</td>
<td>86&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Firm pelvis</td>
<td>Body weight/length</td>
<td>0.66</td>
<td>–68</td>
</tr>
<tr>
<td></td>
<td>Body weight</td>
<td>0.59</td>
<td>–45</td>
</tr>
<tr>
<td></td>
<td>Trunk mass/length</td>
<td>0.65</td>
<td>–45.9</td>
</tr>
<tr>
<td></td>
<td>Trunk mass</td>
<td>0.59</td>
<td>–</td>
</tr>
</tbody>
</table>
TABLE 5.18 Correlation for Female Subjects—Base Stiffness Zones

<table>
<thead>
<tr>
<th>Bed Base Type</th>
<th>Anthropometrical Characteristic</th>
<th>$r^2$</th>
<th>Intercept</th>
<th>Slope</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firm pelvis</td>
<td>Pelvic width/body weight</td>
<td>0.86</td>
<td>−126.8$^a$</td>
<td>32211$^a$</td>
</tr>
<tr>
<td></td>
<td>Waist width</td>
<td>0.85</td>
<td>206.13$^a$</td>
<td>−622$^a$</td>
</tr>
<tr>
<td></td>
<td>Trunk mass/length</td>
<td>0.82</td>
<td>207.84$^a$</td>
<td>−9.56$^a$</td>
</tr>
<tr>
<td></td>
<td>Body weight/length</td>
<td>0.82</td>
<td>207.85$^a$</td>
<td>−4.86$^a$</td>
</tr>
<tr>
<td></td>
<td>Lower trunk mass</td>
<td>0.81</td>
<td>147.88$^a$</td>
<td>−4.76$^a$</td>
</tr>
<tr>
<td></td>
<td>Body weight</td>
<td>0.62</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Trunk weight</td>
<td>0.60</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Waist width/length</td>
<td>0.75</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Lower trunk mass/length</td>
<td>0.74</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Soft shoulder</td>
<td>Waist width/shoulder width</td>
<td>0.65</td>
<td>−70.85$^a$</td>
<td>160.9$^a$</td>
</tr>
<tr>
<td></td>
<td>Shoulder width</td>
<td>0.61</td>
<td>158.7</td>
<td>−339$^a$</td>
</tr>
</tbody>
</table>

$^a p<0.05.$

The magnitude of optimal zone characteristics yet, but it indicates which type of body build requires which type of zone subdivision.

5.2.2.3 Discussion

The results of the different measurement sequences clearly show that a distinction has to be made between male and female subjects, although this is, at present, not the case for 90% of manufactured sleep systems, including the majority of foam mattresses (especially polyurethane), spring mattresses (those consisting of bi-conical and endless springs), and fluid-based sleep systems.

The outcome at this stage is a multiple correlation between the body build of a subject and the type of zones a well-supported mattress should consist of (e.g., whether a softer shoulder zone is necessary or not). The exact magnitude (e.g., the CTBA core value) of these zones cannot be defined yet with a sufficient accuracy, as only two stiffness levels are measured per zone; this zone quantification will take place at the third stage (see Section 5.2.3).
The second stage measurements provide the information that is necessary for the creation of a well-balanced sleep system mix, i.e., a range of sleep systems that covers the entire population. With new concepts of mattress design (e.g., air chambers, see Section 2.1.2.1.9) it is possible to measure a considerable amount of (gradually increasing) stiffness levels for each zone within a limited period of time, as will be done in the third and last measurement stage.

Further, different zones were measured independently, keeping the number of bed parameters as low as possible in order not to blur a potential relationship between anthropometrical characteristics and zone parameters. However, it is clear that different zones influence each other: a firmer shoulder zone, for example, will force the body to cant, loading the pelvic zone with more body weight. Conclusions have to be verified for situations that combine different zone tunings.

Finally, the results show that body dimensions in a first place, and an estimated body weight distribution (based on body dimensions) in a second place, determine deformation of the vertebral column on a sleep system.

Unfortunately, there is no literature available—to the knowledge of the authors—that describes similar tests, which prohibits comparative evaluations.

5.2.3 Stage 3: Influence of Local Modifiability

While previous measurements aimed at zone definition—whether mattress zones are needed, and if so, which zones are required for different population groups—this stage aims at zone quantification. It will define which stiffness values have to be applied to each zone, depending on anthropometrical properties, and verify whether these values are consistent with earlier measurements.

Sleep systems with the ability to adjust or optimize stiffness properties are used, with the advantage of applying optimal settings and measuring each individual, which yields a better correlation—if existing—between anthropometries and optimal bed characteristics.

5.2.3.1 Mattress Stiffness Levels

The number and the magnitude of standard air chamber pressure levels are set, based on previous measurement stages and on a limited number of exploratory measurements (see Section 5.1.3.3.2). Some pressure levels or level combinations can be considered unsuitable for all subjects, as illustrated in Figure 5.23 and Figure 5.24, showing which pressure levels in the shoulder and the pelvic zones cause adverse deformations of the spine; a firm setting
in the shoulder region or a soft setting in the pelvic region causes considerable spinal deformations (as indicated by a weighted parameter average). Settings, therefore, are limited to areas without adverse influences. Also, level combinations (e.g., firm/soft/soft) with undesirable effects (e.g., mattress sagging in the middle) are excluded from subsequent measurements. Using Equation 5.4, air chamber pressure levels can be converted to standard CTBA values.

Table 5.19 summarizes the main directives on how the adjustable zones should be set in order to optimize spine support. First, the shoulder zone has to be soft (pressure level 1 or 2) for all male subjects. Pressures above level 2 lead to deformations of the spine that are unacceptable, no matter what the waist and pelvic zone settings are. For female subjects, the shoulder zone is less important, which is consistent with earlier conclusions; high pressure levels should be avoided.
TABLE 5.19 Optimal Air Chamber Tuning

<table>
<thead>
<tr>
<th></th>
<th>Male Subjects</th>
<th>Female Subjects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder</td>
<td>0–2</td>
<td>0–2</td>
</tr>
<tr>
<td>pressure setting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Waist</td>
<td>6–8</td>
<td>8–10</td>
</tr>
<tr>
<td>pressure setting</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelvic</td>
<td>a,c</td>
<td>b,c</td>
</tr>
<tr>
<td>pressure setting</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ Y = -54.772 + (0.496 \times X_1) - (46.913 \times X_3) + (3871.887 \times X_4) + (4349.819 \times X_5). \]

\[ Y = -363.209 + (1.352 \times X_1) - (1468.930 \times X_2) + (889.468 \times X_3) + (11424.862 \times X_6) + (395.220 \times X_7). \]

\[ X_1 = \text{weight (kg)}; X_2 = \text{waist width (m)}; X_3 = \text{pelvic width (m)}; \]
\[ X_4 = \text{shoulder width/weight (m/kg)}; X_5 = \text{waist width/weight (m/kg)}; X_6 = \text{pelvic width/weight (m/kg)}; X_7 = \text{waist width/pelvic width (—)}. \]

As for the waist zone, most women have a small waist width to pelvic width ratio, which explains a high optimal pressure level (9–10) for females. This ratio almost equals 1 for men, and less extra support is needed (optimal pressure between 6 and 8) in this region. A pressure level less than 6 gives no support to the spine, causing even a male subject to sag into the mattress.

As for the pelvic zone, the pressure setting is highly dependent on specific anthropometrical parameters, which requires a mathematical model to define the optimal pressure adjustment. A multiple correlation was set for both male and female subjects, as illustrated in Table 5.19, with \( Y \) the pressure level and \( X_i \) the different anthropometrical properties. The selected \( X \) variables define 83.90% of the variability of \( Y \) for male subjects and 91.50% for female subjects.

After measuring standard levels, the test person gives his/her subjective impression on how the system should be adjusted until it is comfortable. During the last measurement, the expert adapts the system until the spinal column of the test person is lying in an optimal position.

There is a good match between expert results and results based on standard level measurements, but not with user results, for optimal pelvic zone settings, as illustrated in Table 5.20, which might be due to the subjective character of the user input.

TABLE 5.20 Correlation between Different Measurement Approaches

<table>
<thead>
<tr>
<th></th>
<th>Standard Levels</th>
<th>User Opinion</th>
<th>Expert Opinion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Levels</td>
<td>1</td>
<td>0.65</td>
<td>1</td>
</tr>
<tr>
<td>User Opinion</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 5.21 Optimal Air Chamber Modification for Four Male Population Subgroups

<table>
<thead>
<tr>
<th>Male Subjects</th>
<th>Triangle Shape (Shoulder Width/Waist Width &gt;1.4)</th>
<th>Square Shape (Shoulder Width/Waist Width &lt;1.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (weight &lt;80 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>1</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>8</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>6</td>
<td>Pelvic:</td>
</tr>
<tr>
<td>Heavy (weight &gt;80 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>1</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>8</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>7</td>
<td>Pelvic:</td>
</tr>
</tbody>
</table>

### TABLE 5.22 Optimal Air Chamber Modification for Four Female Population Subgroups

<table>
<thead>
<tr>
<th>Female Subjects</th>
<th>Triangle Shape (Pelvic Width/Waist Width &lt;1.27)</th>
<th>Square Shape (Pelvic Width/Waist Width &gt;1.27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (weight &lt;65 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>1</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>10</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>6</td>
<td>Pelvic:</td>
</tr>
<tr>
<td>Heavy (weight &gt;65 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>1</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>10</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>9</td>
<td>Pelvic:</td>
</tr>
</tbody>
</table>
Based on the results—summarized in Table 5.20—a subdivision of different population groups is made, with resulting guidelines that also can be implemented for a marketing strategy or selling tool. The subdivision is made based upon three criteria: sex, body weight, and body contour type (including shoulder, waist, and pelvic width), resulting in eight different population groups, as illustrated in Table 5.21 and Table 5.22 for male and female subjects, respectively. Air chamber pressure levels can be converted to standard CTBA values using Equation 5.4.

5.2.3.2 Bed Base Influence

In the previous subsection the influence of air chamber pressure level adjustment on the human spine was measured. This second subsection depicts the influence of air chamber pressure level modification in combination with several types of bed bases.

First, how a bed base influences the spine when the air chamber system is set in accordance with the optimal settings generated by the previous measurement sequence was analyzed; this results in an indication of which bases are suited to be combined with zoned mattresses. In conclusion, combining standard air chamber adjustments with bed bases achieves a predominantly positive effect. Negative effects are only measured in two groups, of which one (#8 shows only minor effects. Care should be taken with population group #7, with a slightly higher—but insignificant—negative influence. In these cases, air chamber modification optimization will be needed to achieve a resulting overall positive effect.

Second, how the air chamber system should be adjusted to obtain a correct position of the spine for each base was analyzed. This results in indicating which modification is optimal for each population group. In conclusion, optimizing air chamber adjustments achieves a predominantly positive effect, but for most subjects this is only the case for a part of the bed bases. There are also strong differences between the population groups: people with a pronounced profile need more differentiation, while heavier people with a square profile need more support. When only a minor effect is reached with the first factor (combining bed base with standard air chamber tuning), a distinct positive effect is obtained with the second factor (air chamber adjustment optimizing). Consequently, the joint effect of the two factors is strongly positive when a correct choice of bed base is made. For each group, optimal settings and bed base choice are summarized in Table 5.23 and Table 5.24 for male and female subjects, respectively.

As expected, the most flexible bed bases offer a real solution for male subjects who need it: those with a pronounced profile, especially groups #1 and #3 (see Table 5.24). The support quality obtained by combining air chamber mattresses with flexible bed bases cannot be achieved with air chamber mattresses alone. For female subjects, the differences between the bases are much less significant; therefore, more measurements are required.

On the other hand, other groups (e.g., heavier male subjects, groups #2 and #4 in Table 5.24) show a slightly negative effect with extremely flexible bed bases, because these people need a firm rather than flexible bed base. Objectively, it should be possible to obtain at least similar results with a flexible bed base. But subjectively (based on user input), results are satisfying for all bases, and flexible bases require elaborate air chamber adjustment, so probably less effort is taken in optimizing.
### TABLE 5.23 Optimal Air Chamber Modification + Bed Base Choice for Four Male Population Subgroups

<table>
<thead>
<tr>
<th>Male Subjects</th>
<th>Triangle Shape (Shoulder Width/Waist Width &gt;1.4)</th>
<th>Square Shape (Shoulder Width/Waist Width &lt;1.4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (weight &lt;80 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>0.5</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>8</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>5.5</td>
<td>Pelvic:</td>
</tr>
<tr>
<td>Best Base:</td>
<td>5</td>
<td>Best Base:</td>
</tr>
<tr>
<td>Worst Base:</td>
<td>2</td>
<td>Worst Base:</td>
</tr>
<tr>
<td>Group 1</td>
<td></td>
<td>Group 2</td>
</tr>
<tr>
<td>Heavy (weight &gt;80 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>0.5</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>8.5</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>7.5</td>
<td>Pelvic:</td>
</tr>
<tr>
<td>Best Base:</td>
<td>5</td>
<td>Best Base:</td>
</tr>
<tr>
<td>Worst Base:</td>
<td>3</td>
<td>Worst Base:</td>
</tr>
<tr>
<td>Group 3</td>
<td></td>
<td>Group 4</td>
</tr>
</tbody>
</table>

### TABLE 5.24 Optimal Air Chamber Modification + Bed Base Choice for Four Female Population Subgroups

<table>
<thead>
<tr>
<th>Female Subjects</th>
<th>Triangle Shape (Pelvic Width/Waist Width &gt;1.27)</th>
<th>Square Shape (Pelvic Width/Waist Width &lt;1.27)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light (weight &lt;65 kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoulder:</td>
<td>0.5</td>
<td>Shoulder:</td>
</tr>
<tr>
<td>Waist:</td>
<td>10</td>
<td>Waist:</td>
</tr>
<tr>
<td>Pelvic:</td>
<td>6</td>
<td>Pelvic:</td>
</tr>
<tr>
<td>Best Base:</td>
<td>1</td>
<td>Best Base:</td>
</tr>
<tr>
<td>Worst Base:</td>
<td>4</td>
<td>Worst Base:</td>
</tr>
<tr>
<td>Group 5</td>
<td></td>
<td>Group 6</td>
</tr>
</tbody>
</table>
5.2.3.3 Discussion

By combining air chambers and a bed base, more parameters influence the position of the spine, so a larger test group is needed in order to describe statistically the influence of this wide variety of parameters for all population groups.

Further, test persons were only measured in a lateral position (1) because 75% of the people sleep in a lateral position and (2) because the influence of the body profile makes this position the most critical one. The advised settings are only suitable for a lateral position (e.g., the shoulder zone will be too soft when changing to other postures). To avoid this problem, one might decide to strive for a less extreme air chamber adjustment instead of aiming for optimal settings, while still reaching a very good effect thanks to a good choice of air chambers+base combination.

As the results are only based on a very limited sample for some of the population subcategories, while the influence of a wide variety of parameters is described (taking both mattress and base into consideration), care should be taken in interpreting these results. Consequently, it is not advisable to use the results for analyzing specific subgroups (e.g., back patients) or relations (e.g., the relation with age, which is an important factor [De Koninck et al. 1992]). Unfortunately, there is no literature available to the knowledge of the authors that describes similar experiments, which excludes comparative evaluations.

5.2.4 Conclusion

Both “input” and “output” parameters were monitored in order to obtain a complete picture in the course of analyzing the vertebral column of a subject on a sleep system. Input parameters were subdivided into two classes: anthropometrical characteristics and sleep system properties. Output parameters affecting the position and orientation of the spine were summarized in one single number (i.e., the weighted parameter average WA). Each of three measurement stages compared sleep systems that only differ in a limited number of properties, in order to facilitate the succession of measurements and to simplify the determination of less relevant parameters. While only predetermined systems were used in the beginning, adjustable types were measured at a later stage. The acquired knowledge at the end of each stage enabled the performance of more complex measurements at the next stage.

The first measurement stage was simple and provided straightforward general guidelines on the influence of a firmer or softer mattress core on the shape and position of

\[
\begin{array}{ccc}
\text{Group 7} & & \text{Group 8} \\
\text{Heavy Shoulder:} & 0.5 & \text{Shoulder:} & 1.5 \\
\text{Waist:} & 10 & \text{Waist:} & 8 \\
\text{Pelvic:} & 9 & \text{Pelvic:} & 8.5 \\
\text{Best Base:} & 1 & \text{Best Base:} & 2, 3, 4, 5 \\
\text{Worst Base:} & 5 & \text{Worst Base:} & 1 \\
\end{array}
\]
the vertebral column. For the greater part of the test group, a satisfactory result could be obtained. The measurements show that an extra-soft mattress or an extra-firm mattress, which is commonly believed to be beneficial for low back pain is not a good choice for the majority of people. The most significant outcome, however, was the difference between male and female subjects, and the fact that female subjects with a pronounced body contour (see Figure 5.25) and male subjects with an athletic body build (see Figure 5.26) are not sufficiently supported by sleep systems with an optimized, but homogeneous stiffness.

The second measurement stage put emphasis on the response of the vertebral column of different population groups to different kinds of mattresses and bed bases, especially when sleep systems are subdivided into several zones in the cranio-caudal direction, each having different local material properties. The outcome was a multiple correlation between the body build of a subject and the type of zones of a well-supported mattress. The exact magnitude of these zones cannot be defined yet because it requires additional measurements.
For that reason, the third and last measurement stage aimed for zone quantification; it defined which stiffness values have to be applied to each zone, depending on anthropometrical properties, giving a clear insight in the underlying relationships. Figure 5.27 illustrates optimal back support for four female population subgroups; Figure 5.28 represents optimal back support for four male population subgroups (see Section 5.2.3). To obtain a refined and more accurate subgroup subdivision for the female population, a larger number of measurements are required. These measurements can possibly be replaced by computer simulations, as was discussed in Chapter 4.

![Optimal back support for female population subgroups.](image1)

**FIGURE 5.27** Optimal back support for female population subgroups.

![Optimal back support for male population subgroups.](image2)

**FIGURE 5.28** Optimal back support for male population subgroups.

Based on the final results, it is possible to predict how a certain person $x$ will be supported by a sleep system $y$, while a correlation is established between anthropometrical properties and optimal sleep system characteristics. This information
can be used for development purposes (e.g., to define new materials or material combinations that better fit a certain population or to integrate individualized information into a product), while the resulting guidelines can be implemented in a marketing strategy or selling tool, as are discussed in Chapter 6.

There are limitations of the described measurements that should be accounted for in future work. For example, only normal healthy people are measured, so a next step could be to continue with this research approach by recruiting a symptomatic patient population of people with chronic back pain or scoliosis. It also might be beneficial to recruit a participant population that has a more equally distributed age profile, as it is possible that age distribution could have certain characteristic outcomes. Furthermore, instantaneous exposures are made instead of nightlong registrations in order to save measuring time; future measurements could be conducted as a sleep study to focus more on personal characteristics instead of population classes.

Finally, it should be stressed that the measurement results provide a connection between anthropometrical characteristics and optimal sleep system properties in general and, therefore, only general guidelines for the design of new systems (for development) or for the selection of an adequate bed (in a store) for different population classes. Therefore, care should be taken when extrapolating these figures:

• The first error might be to extrapolate the figures to the (quantitative) design of new sleep systems that consist of different kinds of materials (e.g., pocket spring mattresses) than those that were described and tested throughout this chapter. In other words, general guidelines (e.g., concerning the difference between male and female subjects) are transferable to any sleep system for normal, healthy subjects, but new measurement or modeling sequences are needed for the design of new sleep systems.
• The second error might be to extrapolate the figures—which are meant for population classes—to individuals, especially to those with extreme body dimensions. When interpreting the results too strictly, and designing sleep systems like orthotics, they will fit for only a certain body position and for a fixed location. Because people usually sleep in multiple positions, the mattress has to deal with different (and often conflicting) support needs. For example, choosing an extra-soft shoulder zone for an individual with extremely wide shoulders (to support him or her correctly in a lateral position) will result in inadequate body support in a supine position. Also, the asymmetry between right and left side sleeping can play a role. In conclusion, the provided guidelines should be interpreted in general, and care should be taken when applying them to individuals, especially to those with specific body dimensions or disorders (e.g., scoliosis).

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6

Guidance to the Optimal Bed

The importance of a bed with respect to the physical quality of sleep is emphasized in Chapters 1 and 2. These two chapters showed that an insufficiently adapted sleep system (i.e., mattress+base+pillow) supports the human body unsatisfactorily, which might result in low back pain.

In order to evaluate the shape of the spine during bed rest, several measurement and modeling techniques were selected in Chapters 3 and 4, while Chapter 5 discussed how these techniques are able to give insight into the influence of body dimensions and body weight distribution on the position of the vertebral column on a sleep system. As a result, people are assigned to population classes, each with specific demands for optimal sleep system characteristics.

The main problem at present remains that result processing is extremely time-consuming, for both measurements and simulations, while it is difficult for a nonexpert to interpret the results. The first section of this chapter condenses the results into a set of practical guidelines that can be used by both bed designers and customers. The second section describes the possibilities for automating these procedures (see Chapters 3 to 5) to overcome the problems of result processing, and an attempt is made to replace the expert’s decision process with neural networks and to automate most procedures. The third section describes how results can be represented in a comprehensible way, so that they can be implemented as a marketing strategy or selling tool.

6.1 Practical Guidelines

6.1.1 General Guidelines

6.1.1.1 Physical Factors

The following recommendations are related to the physical factors that were described in Chapter 1 (Section 1.1) and can help choose an adequate sleep system. These recommendations are intended for normal healthy adults, but not necessarily for children or persons experiencing medical problems. For people suffering from sleeping disorders (such as low back pain or narcolepsy), specific sections are added (see Sections 6.1.2 to 6.1.5).

6.1.1.1.1 Recommendations Regarding Anthropometrical Differences

6.1.1.1.1.1 Soft-Firm—Measurements (see Chapter 5) illustrate that the use of different weight classes (e.g., a firmer mattress for people with a higher body weight) improves
spinal alignment significantly. However, measurements also show that an extra-soft mattress or an extra-firm mattress—which is commonly believed to be beneficial for low back pain—is not a good choice for the majority of people.

When a sleep system is too soft, places where body weight is concentrated (e.g., the hip zone) will sag into the mattress. Some muscles may be well relaxed in this position, but the spine certainly will not; when lying in a supine position, the pelvis will cant backward resulting in an excessive and unnatural smoothening of the lumbar lordosis. At the anterior side, intervertebral disks will be compressed, while soft tissues (e.g., ligaments) will be under tension at the posterior side. When sleeping in a lateral position the spine will be loaded asymmetrically.

When sleeping on too firm a mattress, the spinal column will be supported incorrectly; for a lateral position only places with a large body width—the shoulders and the hip zone—will be supported. The lumbar region will bend down, especially with people who have a more pronounced contour (e.g., women). In a supine position the pelvis will first cant forward under influence of muscle tension in the legs; after muscle relaxation, it will cant backward as is the case on soft mattresses. The consequent flattening of the lordosis is less pronounced and harmful as compared to a mattress that is too soft, which means that sleeping too soft is worse than sleeping too firm. A typical solution for a mattress that is too soft (e.g., because it is worn down) is to put a stiff wooden board under the mattress, which can only serve as a temporary solution because it insufficiently corrects the support properties and may cause ventilation problems.

Even if an extra-soft mattress or an extra-firm mattress would offer good support in a specific posture, the use of this type of mattress is not encouraged, because people usually sleep in multiple positions. For example, choosing an extra-soft shoulder zone for an individual with extremely wide shoulders (to support him or her correctly in a lateral position) will result in inadequate body support in a supine position.

In addition, beds that are constructed for two people, such as queen-size beds or similar have an understructure that spans the entire width of the bed. To avoid any vertical deflection in the middle, these structures need the aid of a central leg. European beds are often split and have a central leg set up by default to avoid tilt toward the center of the bed—not always successfully, however.

6.1.1.1.2 Male-Female—Measurements (see Chapter 5) illustrate the important difference between male and female subjects: dimensions concerning the shoulder area (such as shoulder width) are closely related to spinal alignment for male subjects, while dimensions concerning the pelvic area (such as waist width/pelvic width) are most relevant for female subjects. This implies that for female subjects good support in the pelvic area is most important, while male subjects need good support especially in the shoulder area.

6.1.1.1.3 Stiffness Zones or Not—Mattresses or bed bases with different stiffness zones (e.g., a softer shoulder zone) are a good option for all people, but not mandatory for the entire population. For a large number of people relatively good support can be obtained with sleep systems with homogeneous stiffness (see Chapter 5).

Nevertheless, a soft shoulder zone will improve spinal alignment for male subjects, and this type of zone is mandatory for subjects with an athletic body build (large shoulder or thorax width). A firmer pelvic zone is less important for male subjects, but still is advisable.
For female subjects, a firm pelvic zone will improve spinal alignment, and this type of zone is mandatory for subjects with pronounced body contours (small waist width with respect to pelvic width). A firmer waist zone is advisable for female subjects, but a soft shoulder zone is less important.

Furthermore, in order to avoid any asymmetric loading of the spine, it is important that the feet are positioned higher than the pelvis (see Chapter 2). Supporting the lower thigh-knee-calf transition more firmly encourages lateral stability.

In conclusion, male and female subjects with extreme body dimensions will benefit most from a subdivision of the sleep system into different stiffness zones, or from a custom-made bed. These adjustments can be made to the mattress or to the support structure. A combined adjustment (e.g., softer shoulder zone in both mattress and support structure) is only necessary in the case of extreme body dimensions (e.g., very wide shoulders).

6.1.1.2 Recommendations regarding Environmental Aspects

6.1.1.2.1 Microclimate—The main climate parameters are temperature and humidity, both inside and outside the bed, and in a continuous interaction with the person(s) staying in the bedroom. Moisture has to be transported to the environment in order to avoid a clammy feeling at the mattress surface, to avert mildew formation at the mattress bottom, and to prevent decubitus ulcers, since a moist skin is rough and therefore more sensitive to shear forces. Although some mattress manufacturers might claim the opposite, both synthetic and natural latex cores have an impenetrable skin, which gives them poor ventilation properties compared to spring mattresses. Body movement during sleep does not significantly improve the ventilation capability of a mattress. For dry weather, room ventilation can be improved by opening a window. Further, warm humid air has to be prevented from floating into the bedroom, since it might condense, thus obstructing mattress ventilation and creating a seedbed for house dust mites (see Section 6.1.1.2). Of course mattress maintenance is an important issue for the preservation of its ventilation properties.

The main part of temperature regulation takes place by evaporating water through breathing. The remaining warmth produced by the human body is given out through the skin. Body temperature should stay constant during sleep. When heat insulation is too low, the body will cool off, resulting in muscle stiffness and sleeping disorders. When heat insulation is too high, transpiration will increase, resulting in too high relative humidity and consequent sleep disturbances. An optimally insulating sleep system ensures a bed temperature between 28° and 32°C, allowing the contact temperature to stabilize between 30° and 35°C. The insulating capabilities of a bed depend mainly on the core of the mattress and on its top layer(s). A core consisting of natural latex or polyurethane has higher insulation than springs (e.g., pocket springs).

In conclusion, correct support qualities—which are of primary importance—can be obtained for different kinds of mattresses by defining material properties correctly (springs, latex, polyurethane, etc.). The choice of material can depend on personal preferences (some people prefer a softer feeling, such as obtained with a latex mattress, while others prefer a firmer feeling, such as obtained with a spring mattress) or on microclimate regulation (some people prefer good insulation, such as obtained with a
latex mattress, while others prefer good ventilation, such as obtained with a spring mattress).

6.1.1.1.2.2 Body Weight Distribution—When concentrating on normal healthy people and thus on the prevention of eventual disorders, back-support qualities are of primary importance. Other purposes are secondary, keeping in mind that peak values (e.g., pressure points) should be avoided. Only in the case of hospital applications (where people are forced into a recumbent position for a longer period of time), do pressure relief and body weight distribution become of primary importance.

Furthermore, there is no coupled relation between pressure relief and spinal alignment, which means that pressure-relieving mattresses in general do not necessarily support the spine correctly. The reason lies in the fact that body contour is not related linearly to weight distribution, as illustrated in Figure 6.1. The human body is both wider and heavier in the pelvic zone (with respect to other parts of the body), but this is not true for the thoracic zone; due to the presence of the lungs, our body is wider but not heavier at this location.

As a result, mattresses that focus on body weight distribution will deform more at places where weight is concentrated, which causes zones with less

![FIGURE 6.1 Body weight-body contour difference.](image1)

weight concentration to rise. The heavy pelvic zone consequently will cause the mattress to sag, while the lifted thorax zone will be loaded asymmetrically (see Figure 6.2).

![FIGURE 6.2 Mattress sagging.](image2)
Measurements originating from a pressure mattress (measuring body weight distribution) nevertheless can be applied (see Section 6.3.2) in relation to body support during sleep, as long as an expert interprets the measurement results, and no coupled relation between pressure relief and spinal alignment is made for the entire body.

6.1.1.2 Physiological Factors

Physiological reactions of the human body are often a response to the physical condition of the body in its environment. As a result, many of the aspects described below (e.g., respiratory problems) are closely related to the physical factors that are described above (e.g., body posture).

The following recommendations concern the physiological factors listed in Chapter 1 and can help achieve sleep and the benefits it provides. These recommendations are intended for normal healthy adults, but not necessarily for children or persons experiencing medical problems.

6.1.1.2.1 Circadian Clock

Our sleep-wake cycle is regulated by a “circadian clock” and the body’s need to balance sleep time and wake time (Van Gelder 2004). The distinct rise and fall of body temperature, plasma levels of certain hormones, and other biological conditions measure these rhythms (National Sleep Foundation 2002). All of these are influenced by our exposure to sunlight and help determine when we are asleep and when we are awake. It is important, therefore, to keep a regular bedtime and wake time, even on weekends.

When traveling to a new time zone, our circadian rhythms are slow to adjust and remain on their original biological schedule for several days, which is known as jet lag. Some simple behavioral adjustments before, during, and after arrival can help minimize some of the side effects of jet lag, such as anticipating the time change for trips by getting up and going to bed earlier several days prior to an eastward trip and later for a westward trip. Furthermore, daylight is a powerful stimulant for regulating the biological clock (Yoon et al. 2002), so use blindfolds to block out unwanted light while sleeping and try to stay outdoors while awake.

6.1.1.2.2 Smoking, Eating, and Drinking

Caffeine is a stimulant, which means it can produce an alerting effect. Caffeine products, such as coffee, tea, colas, and chocolate, remain in the body on average for 3 to 5 hours, but they can affect some people up to 12 hours later. The results of several studies confirm the widely held belief that coffee consumption interferes with sleep quantity and quality (Shilo et al. 2002). In addition, some articles suggest the consumption of caffeine influences the excretion of 6-SMT (melatonin, see Section 6.1.1.2.6), which is related to the light-dark cycle of our body. Individuals who suffer from sleep abnormalities should avoid caffeine during the evening hours to improve sleep quality.

Nicotine is also a stimulant. Smoking before bed makes it more difficult to fall asleep. When smokers go to sleep, they experience withdrawal symptoms from nicotine, which also cause sleeping problems. Nicotine can cause difficulty falling asleep and problems
waking in the morning, and may also influence REM sleep (Gillin et al. 1994). However, the literature suggesting an effect of nicotine treatment on sleep is contradictory, perhaps because different doses and routes of administration were used (Salin-Pascual et al. 1999). On the other hand, literature suggesting that smoking can alter pH and propagate accelerated degeneration of the intervertebral disks (Goldberg et al. 2000) is consistent.

Many people think of alcohol as a sleeping aid because of its sedating effect, but there are large individual differences in the sedation and impairment effects of ethanol, related to a subjects’ basal level of sleepiness/alertness (Zwyghuizen-Doorenbos et al. 1990). In fact, alcohol actually disrupts sleep (Herzog and Riemann 2003), causing nighttime awakenings (e.g., due to the fact that nighttime alcohol ingestion influences nocturnal breathing in patients with sleep apnea syndrome or respiratory diseases). Also, the nocturnal heart rate significantly increases in people who are under the influence of alcohol.

Eating or drinking too much may make you less comfortable when settling down for bed. It is best to avoid a heavy meal too close to bedtime. A night eating syndrome can be identified with consumption of food just before going to sleep—or during sleep time—and no consumption (or only a little) for breakfast (Adami et al. 1997). According to these criteria, 3.5% of lean subjects should be considered as affected by night eating syndrome. Also, spicy foods may cause heartburn, which leads to difficulty falling asleep and discomfort during the night.

As a result of a period of fasting (such as Ramadan), small body mass loss and dehydration are frequent. Some studies describe an increased irritability and incidences of headaches, with sleep deprivation and lassitude prevalent. The majority of the studies on this subject have found significant metabolic changes, but few health problems (such as enduring sleeping disorders) arising from a fast (Leiper et al. 2003).

6.1.1.2.3 Headaches

Next to back pain, headache is the second most common pain. Of those who experience the onset of headaches during sleep, 55% report having sleeping disorders (National Sleep Foundation 2002). In particular, sleep is related to tension or migraine headaches (i.e., throbbing pain with blood vessels tightening and opening). Migraine headaches can occur following sleep deprivation or too much sleep. Chronic morning headaches are a good indicator of major depressive and insomnia disorders.

In addition to this, headaches have also been associated with sleep disorders such as sleep apnea. Some authors suggest that treatment of the associated disorder (e.g., snoring) may reduce these headaches. Recent articles, however, suggest that (morning) headaches are not specific to sleep-related breathing disorders (Ohayon 2004; Jensen et al. 2004), such as the obstructive sleep apnea syndrome.

Patients with poorly defined nocturnal or awakening headaches should undergo polysomnography to exclude a treatable sleep disturbance.

6.1.1.2.4 Respiration Problems

Snoring (i.e., a breathing noise that occurs during sleep) is a common problem among all ages and both genders. Persons most at risk are males and those who are overweight, and
it usually becomes more serious as people age. Snoring can cause disruptions to the partner’s sleep and is also associated with cardiovascular problems such as high blood pressure, headaches, and diabetes. Treating these associated problems may treat the cause of snoring (overweight persons can benefit from losing weight), whereas the effect of snoring can be limited by sleeping in a lateral position, because blockage of the air passage between the upper soft palate and the throat or base of the tongue is less likely to occur in this position.

As it becomes harder to breathe and snoring becomes worse, breathing may actually stop, which is a sign of apnea. The specific therapy for sleep apnea is tailored to the individual patient based on medical history, physical examination, and the results of polysomnography (see Chapter 1). Medications are generally not effective in the treatment of sleep apnea.

“Nasal continuous positive airway pressure” is the most common effective treatment for sleep apnea. In this procedure, the patient wears a mask over the nose during sleep, and pressure from an air blower forces air through the nasal passages. The air pressure is adjusted so that it is just enough to prevent the throat from collapsing during sleep. Dental appliances that reposition the lower jaw and the tongue have been helpful to some patients with mild to moderate sleep apnea, or who snore but do not have apnea. Some patients with sleep apnea may need surgery. Although several surgical procedures are used to increase the size of the airway, at present none of them is completely successful or without risks. Without going into detail, examples of surgical techniques are somnoplasty (i.e., reducing the size of the soft palate with radio wave energy), uvulopalatopharyngoplasty (i.e., tightening the soft palate and removing the uvula and the tonsils [if present]), and tracheostomy (i.e., creating an opening through the neck into the trachea [windpipe] and placing a tube through this opening to provide an airway).

6.1.1.2.5 Cardiovascular Problems

Cardiovascular problems are often closely related to other sleep-disturbing factors such as the intake of nicotine and alcohol (see Section 6.1.1.2.2). Some researchers (Ha et al. 2001) also mention shift work. Blood pressure and heart rate variability show significantly increasing trends according to shift work duration, which suggests that negative health effects on the cardiovascular system arise from shift work. Cardiovascular disease and heart attacks also occur more frequently in certain occupational groups who work shifts, but the way in which shift work affects the heart is not clear. Sleep apnea (see Section 6.1.1.2.4) may be an underlying cause of heart disease, high blood pressure, or other heart problems. Cardiovascular problems also are often related to thermoregulation. As a result, the treatment of cardiovascular problems (e.g., during sleep) is closely related to the treatment of its origin (e.g., extreme obesity).

For some types of cardiovascular problems, such as poor blood circulation, a mattress offering good pressure distributing qualities is important. Next to this, it might be helpful to raise the foot side of the bed to facilitate the backflow of the blood to the heart (see Figure 6.3), e.g., in the case of swollen legs due to poor blood circulation.
6.1.1.2.6 Hormones

Melatonin is a natural hormone made by the body’s pineal gland, which is a tiny structure located at the base of the brain. As melatonin production rises, alertness and body temperature decrease. Melatonin levels drop again at the end of the night. Melatonin levels are related to the light-dark cycle not just for people but also plants, and animals that keep alert during the day. As a consequence, bright light administration is able to significantly suppress melatonin levels, for example, during night work (Lowden et al. 2004).

The production and sale of synthetic melatonin to promote sleep, however, are not regulated, and side-effects (such as safety, interactions with drugs, and long-term effects) are not clear.

Menopause is a source of potential sleeping problems; the hot flashes (Shaver et al. 1988) and associated breathing changes that most women experience during this time appear to disturb sleep and may lead to daytime fatigue. Seventy-five percent of menopausal women suffer from hot flashes, on average for 5 years. Paced respiration (i.e., scheduled breathing) at the beginning of hot flashes significantly reduces the frequency of hot flashes. Another approach involves hormonal treatment with progesterone and estrogen (Nelson 2004). Naps may help alleviate fatigue, too, but if insomnia is a problem, naps should be avoided, because they can contribute to night-time sleeping difficulties.

6.1.1.2.7 Drugs

In addition to the influence of melatonin and menopause, quality of sleep is often affected by the use of drugs. In the case of pain, both doctors and patients frequently consider narcotic drugs or medications, such as codeine. Hypnotics (i.e., drugs that promote sleep) may be prescribed to help those with sleeping difficulties. Although they may have little effect on pain, the improved sleep can help daytime fatigue. When pain is accompanied by difficulty sleeping, a combination of products may be needed, or a single product that both reduces pain and promotes sleep.

Even though many of the cited products are relatively low cost, easy to get, and often effective, it is not clear how some drugs, such as tranquilizers, or some combinations of drugs can interact with pain and sleep; additional problems can develop when drugs
interact with each other. Individuals suffering from sleeping problems should discuss carefully with their physicians the medications they are taking.

6.1.1.2.8 Allergic Reactions

House dust mites are minuscule spiders that populate mattresses, carpets, curtains, and pillows in large quantities. A house dust mite allergy is not originated by dust or by the mites themselves. The real cause lies in the allergen “Der PI” which is produced in the intestinal canal of the mites when degrading organic dirt—especially human skin peels—biologically (Mosbech et al. 1991).

Complete extinction of the mites is virtually impossible, but allergic symptoms can be decreased by keeping the air humidity lower than 55% or by limiting exposure to the excrements by correct and thorough sanitation: allergen-proof polyurethane coating around the mattress core and a synthetic top layer that can be taken off and washed at a temperature above 60°C. Mattresses should be easy to maintain.

In addition to a house dust mite allergy, there are many allergies (e.g., latex allergy) that might arise due to chemical substances that are present in the sleep system or environment.

6.1.1.2.9 Exercise

In general, exercising regularly makes it easier to fall asleep and contributes to sounder sleep. However, exercising sporadically or right before going to bed will make falling asleep more difficult. In addition to making us more alert, our body temperature rises during exercise and it takes as much as 6 hours to begin to drop. A cooler body temperature provides a signal that it is time to sleep. It is advisable to finish exercise at least 3 hours before bedtime. Late afternoon exercise is the perfect way to help you fall asleep at night (National Sleep Foundation 2002).

Although muscle relaxation is an important factor during sleep, there is no scientific evidence that there is a coupled relation between muscle activity minimization and body support optimization (and spinal alignment). The literature (Lahm and Iaizzo 2002) confirms that no clear relation between spinal alignment and EMG (electromyography) has been distinguished so far. EMG measurements are used to detect the electrical signals associated with muscle contraction (see Chapter 3). By measuring and analyzing EMG signals on different sleep systems, some additional information is provided on the condition of the human body, but no prediction can be made about which system offers the best support qualities, unless spinal alignment itself is evaluated. EMG measurements nevertheless can be useful, as long as an expert interprets the measurement results, and no coupled relation between EMG and spinal alignment is made.

6.1.1.3 Psychological Factors

The following recommendations are related to the psychological factors that are described in Chapter 1. These recommendations are intended for normal healthy adults, but not necessarily for children or persons experiencing medical problems.
6.1.1.3.1 Sleep-Promoting Environment

The sleep environment should be designed to establish the conditions that are needed for sleep—cool, quiet, dark, comfortable, and free of interruptions. The room should be checked for noise or other distractions, including a bed partner’s sleep disruptions such as snoring, light and a dry or hot environment. These factors are clearly related to physiological factors, but they could be a source of annoyance or irritation as well. Furthermore, make the room attractive and inviting for sleep.

6.1.1.3.2 Bedroom-Sleep Association

Use a bed only for sleep to strengthen the association between bed and sleep. If you associate a particular activity or item with anxiety about sleeping, omit it from your bedtime routine. For example, if looking at a bedroom clock makes you anxious about how much time you have before you must get up, move the clock out of sight.

6.1.1.3.3 Relaxation

A relaxing, routine activity right before bedtime conducted away from bright lights sends a signal to the body that it is time to go to sleep and will make it easier to fall asleep. Avoid arousing activities before bedtime (such as problem-solving activities), and try an activity that is relaxing, such as soaking in a hot tub, reading, or listening to music. (Care should be taken to take a hot bath early enough that you are no longer sweating or overheated.) If you do not fall asleep within 15 to 20 minutes of going to bed and turning out the lights, it is best to get out of bed and do another relaxing activity until you feel sleepy again. If you are unable to avoid tension and stress, it may be helpful to learn relaxation therapy from a trained professional.

6.1.2 Low Back Pain

Problems related to back pain are responsible for people taking more days off work than any other orthopedic complaint. This subsection describes common types of low back pain and how choosing an adequate sleep system or sleeping posture could bring relief.

Most complaints can be categorized as functional—because of the mechanical origin—and refer to the lumbar area (see Figure 6.4), which is exposed to pressure and tension forces mounting up under the load of body weight and movement. Intervertebral disks function as a shock absorber, and the vertebral column is typically overloaded by maintaining a harmful posture, by repeating fatiguing movements, or by carrying out daily activities improperly, thus causing or aggravating this particular kind of low back pain. Ligaments and joints also can be damaged by this overload.

In addition to mechanical factors, genetic, chemical, social, nutritional, and psychological factors can influence the onset of low back pain (Holm 1993). This subsection, however, only describes those types of low back pain that
have a mechanical origin, because only in these cases can a relation with the sleep system or the sleeping posture be made.

Care should be taken not to generalize the recommendations given below, since it is difficult to define exactly where the pain is coming from (ligaments, intervertebral disks, etc.), even for low back pain with a mechanical origin, due to the complexity of the sensory system that innervates the structures (i.e., supplies the structures with nerves) in the lumbar region. As a result, a patient’s clinical presentation may initially be misleading to the diagnostician, because apparently similar pain patterns are produced by different afflictions.

6.1.2.1 Low Back Pain Classification

Different anatomical structures (see Section 1.1.1.1 for the anatomy of the spine) can be responsible for lumbar pain, each producing a distinctive clinical profile (Sizer, Jr. et al. 2001). First of all, pain can arise from the intervertebral disk (indicated as 1 in Figure 6.5), either acutely as a primary disk-related disorder, or as a result of the degradation associated with chronic internal disk disruption (secondary disk-related disorder). In either case, the greatest pain provocation will be associated with movements and functions in the sagittal plane. Second, lumbar pain also can arise from afflictions within the facet joint mechanism (indicated as 2 in Figure 6.5), which will produce the greatest pain provocation during three-dimensional movements. Younger individuals with low back pain are commonly afflicted with a primary disk-related disorder (such as protrusions and prolapses), caused by acute mechanical (or chemical) changes in the disk, while relatively older individuals (i.e., over 45 years old) are more confronted with secondary disk-related disorders. Furthermore secondary disk pathology often arises from previous episodes of primary disk-related disorders.

Most complaints relate to the intervertebral disk, which consists of rings of ligaments (annulus fibrosus) around a gel-filled center (nucleus pulposus), as illustrated in Figure 6.6. The cartilaginous endplate is a thin structure
(approximately 1 mm thick) that constitutes the border between the intervertebral disk and the vertebral body. It is composed of thin layers of cartilage that demonstrate parallel, horizontal collagen fibers.

The annulus fibrosus, the nucleus pulposus, and the cartilaginous endplates can cause back pain. An endplate can fracture during acute traumatic loading or demonstrate gradual flattening in response to disk degeneration and accompanying intradiscal water loss, which may cause slipping (or herniation) of nuclear material into the vertebral body (Weishaupt et al. 1998). Also, a partial rupture of the surrounding ligaments (annulus fibrosus) can cause the disk nucleus to expand, with the risk of reaching nerve roots from the spinal cord, which is called slipped disk (or disk hernia).

As mentioned earlier, a patient’s clinical presentation may initially be misleading to the diagnostician, so a physician’s clear understanding of the pathoanatomy, physiology,
and mechanics of the lumbar spine can serve as a foundation for clarity in differential diagnosis.

6.1.2.1 Lumbago

Lumbago is a general term used to describe (mostly acute) pain in the lumbar region. Symptoms include pain in the lower back that does not radiate down the legs (cf. sciatica, see Section 6.1.2.1.3), and stiffness in the back, especially in the morning. It is usually a seizure of pain that is short in duration and limited to the central low back region; this pain is greatly aggravated by body movement, especially in attempting to rise from the recumbent posture.

The origin of lumbago varies, but it often occurs in younger people whose work involves physical effort. In these cases, pain is propagated through a macrotraumatic event such as lifting or overuse. Although symptoms resolve spontaneously in 4 to 6 days, the more significant consequence of this breach emerges several years later (e.g., when the cause of an acute lumbago lies in a fracture of the endplates of an intervertebral disk during acute traumatic loading). In these cases, an acute lumbago can convert into a chronic lumbago (e.g., when a fracture of the endplates has caused a disk herniation, see Section 6.1.2.3.1).

Furthermore, lumbago is not uncommon in people of retirement age either. Lumbago can demonstrate osteoporosis (brittle bones) or gradual flattening of the intervertebral disk in response to disk degeneration, which may cause slipping (or herniation, see next section) of nuclear material.

6.1.2.1.2 Disk Disruption

In the case of a healthy disk, no permanent deformation will ensue when a prolonged load is subsequently released. The healthy nucleus serves as a means of energy dissipation and load redistribution, where it behaves like both a solid and a fluid, depending on the stress profile to which it is exposed. Damage (e.g., to the endplate) and subsequent disk alterations produce increased stress peaks (on the annulus) and decreased pressure (in the nucleus) during weight bearing, which may activate further structural disruption. Clinically, these behaviors have been noted with structural changes that render increased space available for the nucleus to migrate. Three levels of disk disruption can be distinguished: disk protrusion (when the nucleus is bulging out the annulus), disk prolapse (when the nucleus is breaking out through the annulus), and disk extrusion (when the nucleus gets outside the annulus).

6.1.2.1.2.1 Disk Protrusion—A disk protrusion is produced when an annular fissure forms from within the disk, which allows the nuclear material to migrate either in a postero-medial or postero-lateral direction (see Figure 6.7).

Because of the rich population of free nerve endings in the annulus, this protrusion produces low back pain. In the event that the protrusion is large
FIGURE 6.7 Postero-lateral (left) and postero-medial (right) disk protrusion.

enough to tension load an adjacent nerve root, the patient may experience lower extremity pain as well, which is called sciatica (see Section 6.1.2.3.1).

6.1.2.1.2.2 Disk Prolapse (Herniation)—A prolapse is similar to a protrusion in that the nuclear material migrates through an annular fissure. However, in case of a prolapse the outer annulus is breached, leaving only the posterior longitudinal ligament intact (which can serve as a source of low back pain as well). The prolapse migration occurs either in a posterior-median or postero-lateral direction (see Figure 6.8) and is commonly associated with a macrotraumatic event.

A prolapse may be associated with a brisk inflammatory response in and around the posterior disk region, but also in the nerve roots from the spinal

FIGURE 6.8 Postero-lateral (left) and postero-median (right) disk prolapse.
cord, which results in a rapid onset of pain in the low back, thigh, lower leg, and foot. These patients will experience a tension that is similar to that observed with a protrusion (e.g., when carrying out trunk movements in the sagittal plane), but is more severe and provocative, which provides the clinician with a distinctive diagnostic indicator for differentiating between protrusion and prolapse. Although prolapse could be viewed as more severe than protrusion, it is potentially eradicated more rapidly and completely vs. protrusion.

Furthermore, the posterio-medial prolapse is considerably more serious than the postero-lateral counterpart, in that the posterior longitudinal ligament is disrupted and the spinal canal is occupied by nuclear material. This condition is most frequent at the L3–L4 and L4–L5 disk levels. The patient describes severe low back pain and bilateral lower extremity pain and will try to adopt a posture with a lumbar kyphosis in an attempt to unload the disk.

Finally, lumbar disk herniations exist in 30% of healthy young adults without symptoms. Many disk hernias heal spontaneously, but they also can cause chronic back pain.

6.1.2.1.2.3 Disk Extrusion—An extrusion is a primary disk-related disorder that demonstrates a disruption of both the outer annulus and the posterior longitudinal ligaments, producing a complete disturbance in the hydrodynamic qualities of the disk and subsequent disk migration outside of the annulus.

After a structural disruption (protrusion, prolapse, or extrusion), stress peaks may be altered further during trunk movements, as intradiscal pressure is elevated during both flexion and extension of the trunk (see Figure 6.9).

Because many patients with these changes experience the greatest symptom provocation during trunk movement in the sagittal plane (flexion or extension), pain relief (e.g., during sleep) will be linked to this movement (see Section 6.1.2.2.2).

![FIGURE 6.9 Flexion-extension.](image)

6.1.2.1.3 Sciatica

Sciatica is the term given to pain down the leg that is caused by irritation of the main nerve into the leg, the sciatic nerve. This pain tends to be centered where the nerves pass
through and emerge from the lower bones of the spine (lumbar vertebrae) and can have various origins, both acute primary disk disorders (e.g., herniation, see previous section) and secondary disorders (e.g., disk degeneration; see next section).

For example, an intervertebral disk is invaded by chemical factors when an endplate is disrupted. These chemical agents aggressively irritate nerve roots, which gradually results in a distribution of low back pain as well as lower extremity pain. This gradual onset of lower extremity pain is more commonly observed in individuals over the age of 45, as compared to the immediate lower extremity pain observed in younger individuals who are suffering from the mechanical irritation associated with an acute primary disk disorder.

6.1.2.1.4 Disk Degeneration

Secondary disk-related pathology can emerge from longstanding primary disk-related disorders (see Sections 6.1.2.1.1 through 6.1.2.1.3), but also from disk degeneration, which results in a reduced disk height and subsequent annular buckling. As a consequence, the axes for motion in the sagittal plane migrate away from the disk, thus promoting aphysiological loading and an increased shearing stress on the disk and facet joints.

In the case of a healthy disk, no permanent deformation ensues when a prolonged load is subsequently released. The healthy nucleus serves as a means of energy dissipation and load redistribution, where it behaves like both a solid and a fluid, depending on the stress profile to which it is exposed. This instantaneous behavioral transition becomes more permanent with aging and degeneration, changing the nucleus pulposus from a fluid-like to solid-like material that is more capable of permanent deformation and failure with chronic loading (Iatridis et al. 1997).

Furthermore, the upper lumbar disk segments (L3–L4 and above) demonstrate a natural aging process that produces increased disk height due to increased nuclear hydrostatic pressure. Conversely, the L4–L5 and L5–S1 segments frequently demonstrate accelerated degeneration accompanied by decreased pressure within the nucleus, decreased stress dissipation, and altered mechanics. As a result, the disk height diminishes and the disk space appears flattened on imaging (e.g., radiography). This process predisposes the L4–L5 segment to greater shear forces, lending this pathway of least resistance to instability.

Some authors (Goldberg et al. 2000) mention that smoking, vibration, or aphysiological motion in the disk (resulting in a compromised circulatory response) can alter pH and propagate accelerated degeneration.

6.1.2.1.5 Facet Joint Pain

As disk height decreases with degeneration (see Section 6.1.2.1.4), a load increase is imposed on the facet joints, which may lead to low back pain because these joints are innervated from different levels.

Facet joint pain produces the greatest pain provocation during three-dimensional movements, but it is difficult to assess an aphysiological motion due to the potential for anatomically based asymmetry. Asymmetries can be observed between the left vs. right
joints in both the transverse and frontal planes and produce a torque preference (Tulsi and Hermanis 1993). Thus, physicians cannot compare left-directed rotatory motions with right rotatory motions. On the other hand, radiologically appreciable gapping between facet surfaces will clinically manifest, e.g., when the patient is prepositioned in rotation while recumbent (Farfan and Gracovetsky 1984).

6.1.2.1.6 Stenosis

In spinal stenosis—which translates as “narrowing”—the spinal canal, which contains and protects the spinal cord and nerve roots, narrows and pinches the spinal cord and nerves. The result is low back pain as well as pain in the legs (see Section 6.1.2.1.3). There are many potential causes for spinal stenosis, including changes in blood flow to the lumbar spine, heredity, and especially aging, which are seen in the majority of stenotic patients who demonstrate degenerative disk and facet joint changes.

Clinical signs and symptoms do not change with altered body position during static stenosis but can change with different positions and motions of the trunk during dynamic stenosis, which is related to a change in canal area during flexion or extension. More specifically, pressure on the spinal cord can increase with standing and walking, while it will typically decrease when sitting or walking with the lumbar spine flexed (see Figure 6.9). As a result, different sleeping postures will also influence pressure.

6.1.2.1.7 Spondylolysis and Spondylolisthesis

A common cause of low back pain is a stress fracture in one of the vertebrae, called spondylolysis, which usually affects L4 or L5. If the stress fracture weakens the bone in such a way that it is unable to maintain its proper position, the vertebra can start to slip out of place, which is called Spondylolisthesis. In adults, Spondylolisthesis is usually caused by degenerative disk disease (see supra) and often affects women over 40 years of age.

6.1.2.1.8 Other Types of Low Back Pain

Finally, patients can experience different symptoms associated with articular (cartilage) degeneration or irritation to the ligaments, dural sleeve, dorsal root ganglion, or chemically irritated lumbar nerve root. Differential diagnosis and treatment of these conditions require a thorough examination and are not discussed here.

6.1.2.2 Low Back Pain: Prevention and Recovery

First of all, there are many ways to prevent low back pain, and to recover from it. This text focuses on posture—sleeping posture more specifically—and how maintaining an optimized sleeping posture can help prevention and recovery from back pain.
6.1.2.2.1 Prevention

The origins of low back pain vary (see Section 6.1.2.1), but mostly occurs in younger people whose work involves physical effort, or in older people who suffer from disk degeneration. In the first case, pain is propagated through a macrotraumatic event such as lifting or overuse. In the second case, age plays an important role. Most types of low back pain, therefore, are not induced during sleep but during daily activities.

On the other hand, low back pain is often aggravated during sleep, due to an insufficiently adapted sleep system or an incorrect sleeping posture. If the vertebral column is supported unsatisfactorily during sleep, the intervertebral disks are loaded in such a way that they are not able to rehydrate, which is needed to regain the elasticity that is lost during (normal) daily activities. Further, the lower pressure in the intervertebral disks enables the cartilage in the facet joints to recover, and muscle relaxation can be obtained on a well-conditioned sleep system on which mobility and stability are promoted (see Chapter 2). The aspect of rehydration is even more important when there is a higher risk for low back pain (e.g., in older people or in people whose work involves physical effort). When intervertebral disks are not unloaded during sleep, daytime and nighttime effects of spine loading accumulate. The facilitation of optimal rehydration during sleep is the key factor in the prevention of low back pain. In other words, the vertebral column should be unloaded as much as possible during the night.

The optimal sleep system for normal healthy people—as most ergonomic specialists suggest it—has to support the human spine so as to optimize load distribution in order to minimize stress. The unloaded reference position practiced throughout this work gives the spinal column the same thoracic kyphosis and lumbar lordosis as in the upright position, yet slightly smoothed by the fact that, in a sleep position, the direction of the gravitation vector no longer coincides with the cranio-caudal direction of the body. A prolongation of the spine of 2% and a consequent smoothing—as during weightlessness—is applied to the reference.

For a lateral posture, optimal support gives rise to the spinal column being a straight line when projected in a frontal plane in order to achieve a symmetrical loading of the spine. The incapability of the human body to control the spinal column actively when sleeping justifies the definition of a correct sleep system for each individual, by defining and combining different materials correctly, depending on anthropometrical characteristics. As illustrated in Figure 6.10, people with different body builds need different beds, which was explained in detail throughout Chapter 5.
FIGURE 6.10 Adjusted sleep system to take anthropometrical differences into consideration.

Next to this straight line in a frontal projection plane, it is important to sleep in such a way that the natural curves of the spinal column (thoracic kyphosis and lumbar lordosis) are maintained. Spinal flexion or extension (bending in a sagittal projection plane; see Figure 6.9) should be avoided in order to shield the intervertebral disk from overload. Three-dimensional positions (caused by a rotation or torsion of the shoulders with respect to the pelvis) should be avoided to shield the facet joints from overload. Chapter 2 (see Section 2.2) explained how different postures (supine, prone, lateral) can influence the shape of the spine. For example, a semi-Fowler’s position with bent knees (135°) and hip joints (45°) results in a relaxed iliopsoas muscle (i.e., the great flexor muscle of the hip joint, divisible into two parts, the iliac and great psoas) and slightly smoothened lumbar lordosis.

In conclusion, the following general rules should be taken into account to guarantee an optimal recovery of a healthy spine during sleep:

1. Lateral bending should be avoided to obtain a symmetrical spine.
2. Flexion/extension should be avoided to unload the intervertebral disks.
3. Torsion of the spine should be avoided to unload the facet joints.

These rules are intended for normal healthy adults, but not necessarily for people who have already developed low back pain.

6.1.2.2 Recovery

The number of people requiring treatment for low back pain, such as a lumbar disk herniation, is high. In addition to treatments such as chiropractic manipulation, operative treatment has become more common in patients with chronic low back pain and a
degenerative disk disease. Whether surgery is done or not, patients need to sleep and wish to experience as little discomfort as possible.

Fortunately, the human body protects the spine—one of its most vital organs—in both a conscious and subconscious way. As a result, our bodies will automatically adopt a posture that when low back pain occurs decreases the load on the affected part of the spine. The objective of the guidelines below is similar to the natural reaction of the human body when pain occurs.

Furthermore, the guidelines below (meant for people with back pain) are partially in conflict with the rules that were cited in the previous paragraph (meant for healthy people). The reason is that the guidelines below aim at temporary local pain relief, while the rules apply for a permanent and global protection of the spine. For example, a moderate spine torsion or flexion may yield a temporary stress relief at the level of injury, but the spinal column will suffer an increased loading at other places, which may lead to other complaints in the long term.

6.1.2.2.2.1 Lumbago—Because lumbago mostly involves acute pain in the lower back that does not radiate down the legs, it is not advisable to adopt a specific posture. The increased loading of the spine as a whole (e.g., as a result of spine extension) would do more harm to the spine than local relief (e.g., by spine extension) would do well for lumbago. The advice is to follow the general rules as much as possible.

When the symptoms of lumbago do not resolve spontaneously in 4 to 6 days (e.g., when the cause of an acute lumbago lies in a fracture of the endplates of an intervertebral disk), it is advisable to adopt a posture that brings pain relief to the origin of the lumbago, which is often a disk disruption or disk degeneration (see below).

6.1.2.2.2 Disk Disruption (e.g., Herniation)—Three levels of disk disruption can be distinguished: disk protrusion, disk prolapse, and disk extrusion (see Section 6.1.2.1.2). In each of these cases, the greatest pain provocation will be associated with movements and functions in the sagittal plane (flexion-extension).

Flattening the lumbar lordosis can bring (temporary) relief, in both the lateral and supine position. (In a prone position it is nearly impossible to obtain lumbar flattening.) In the case of a lateral position, lumbar flattening can be obtained by raising the legs higher (see Figure 6.11), bringing body posture close to a fetal position.

In case of a supine position, lumbar flattening can be obtained by raising the legs higher (e.g., by bringing the body in a Fowlers’ position; see Figure 6.12).

However, it is difficult to maintain this kind of posture—both lateral and supine—for a long period, so at least two positions should be selected for which discomfort is minimized. Furthermore, moving from one position to another (e.g., supine to lateral) should be possible, so two lateral postures
(e.g., left and right) is preferred when a sleep system is fixed in a Fowlers’ position (see Figure 6.12). Also, moving from one position to another should not be painful, which can be done by keeping the leg up during body rotation. A cushion between the knees can facilitate this movement.

In the case of a (asymmetrical) postero-lateral disk disruption (as opposed to a symmetrical postero-median disruption; see Figure 6.7), a slightly asymmetrical spine position may bring relief to the affected intervertebral disk, e.g., in an asymmetrical lateral sleep position (see Figure 6.13).

Many people without back pain automatically adopt this kind of posture as well, because they are sleeping on a surface that is too firm. When they lie in a normal lateral position, the spinal column is supported incorrectly because only places with large body width—the shoulders and the hip zone—are supported. The lumbar region bends down, especially with
people who have a more pronounced contour (e.g., women). To avoid this (harmful) lateral bending of the spine, a posture between a lateral and a prone position (see Figure 6.13) is adopted.

In all of the cases cited above, it is not advisable to adopt an adjusted posture for a long period of time.

Back problems might shift to other regions of the spine, because the cited postures imply an increased loading of the spine as a whole.

6.1.2.2.3 Facet Pain—As disk height decreases with degeneration (see Section 6.1.2.1.4), a load increase is imposed on the facet joints, which may lead to low back pain because these joints are innervated from different levels. Facet joint pain produces the greatest pain provocation during three-dimensional movements. Pain relief can be obtained by adopting similar postures as those described for disk disruption.

6.1.2.2.4 Other Types of Back Pain—Some types of low back pain (e.g., spinal stenosis, irritation to the dural sleeve, dorsal root ganglion) are not directly related to posture. Other types (such as articular degeneration or scoliosis) are directly related to posture but largely depend on the type and location of the origin of the pain. In these cases, an individual approach is needed and will often help. Literature suggests that subjects obtain significant improvement in shoulder and back pain, back stiffness, and quality of sleep after 28 days of prescribed bedding system use as compared with 28 days of personal bedding use. Female subjects and those with lower body weight were more likely to improve significantly than heavier subjects (Jacobson et al. 2002).

In the event low back pain hinders sexual contact between partners, it is advisable to consult a specialist or dedicated literature (Mannekens 1996) for alternative coitus positions (e.g., where the partner with low back pain plays a passive role). Also, it is important not to remain in the same position for a long time (to avoid tension, pain, fatigue, etc.) and to sleep on a stable bed (see Chapter 2).
6.1.3 Cervical Spine and Shoulder Complaints

In contrast to low back pain, cervical spine and shoulder complaints are often initiated during sleep itself, mostly because of lateral bending of the cervical spine. Several factors contribute to good support of the cervical spine and shoulder (see Figure 6.14).

At first, a good pillow is needed (1 in Figure 6.14). This objective can be realized by correctly positioning and shaping deformable cushions (e.g., feather cushions) and by correctly designing less deformable structures (e.g., latex cushions).

Next, the shoulder zone of the mattress or mattress support (2 in Figure 6.14) should be soft enough, especially for people who have large shoulders as compared to the pelvis (male subjects) or to the waist (female subjects). If the shoulders are not able to sink into the mattress, e.g., in case of a mattress that is too firm, both the neck and waist will be supported unsatisfactorily, and too much weight will be carried by the shoulders, resulting in shoulder complaints.

Finally, the neck zone (and the waist zone to a minor degree) of the mattress or mattress support (3 in Figure 6.14) needs to be firm enough, but it should be able to behave independently from the shoulder zone; when indenting the shoulder zone, only local deformation should take place, without exerting too much influence on either the cervical zone or the waist zone. If this is not the case, even the combination of a soft shoulder zone and a well-designed pillow will not be able to support the cervical spine correctly.

6.1.4 Restless Legs Syndrome

6.1.4.1 Occurrence

Restless legs syndrome is characterized by an urge to move the legs, often accompanied by uncomfortable sensations in the legs usually described as a creeping or crawling feeling, but sometimes as tingling, cramping, burning, or just plain pain. Restless legs syndrome is a common and treatable condition. Recent research (Berger et al. 2004) suggests it affects about 10% of adults in North America and Europe, with rates increasing with age.
The cause of restless legs syndrome is still unknown, but the symptoms tend to worsen with age. Pregnancy or hormonal changes may temporarily worsen symptoms. Some cases are associated with iron deficiency anemia or nerve damage in the legs due to diabetes, kidney problems, alcoholism, and Parkinson’s disease. Fluctuations in severity are common, and occasionally the symptoms may disappear for periods of time. Anxiety as bedtime approaches, frustration caused by nighttime awakenings, moodiness and depression, difficulty concentrating, and excessive daytime sleepiness have been reported in association with restless legs.

6.1.4.2 Treatment

Most cases of restless legs syndrome respond well to medical treatment. There are a number of pharmacological treatments, including dopaminergic agents and dopamine agonists. These drugs treat the deficiency of dopamine, a chemical found naturally in the central nervous system where it functions largely as a neurotransmitter.

6.1.5 Narcolepsy

6.1.5.1 Occurrence

Narcolepsy is a chronic neurological disorder that involves the human body’s central nervous system, which is why someone who has narcolepsy may fall asleep at times when he or she wants to be awake. Excessive daytime sleepiness is usually the first symptom to appear, and often the most troubling. In addition to sleepiness, key symptoms of narcolepsy can include regular episodes of cataplexy (sudden loss of muscle control), sleep paralysis (being unable to talk or move for a brief period when falling asleep or waking up), hypnagogic hallucinations (vivid dreams and sounds when falling asleep), and automatic behavior.

Recent literature (Naumann and Daum 2003) has indicated that people with narcolepsy lack a chemical in the brain called hypocretin, which normally stimulates arousal and helps regulate sleep. About 1 in 2000 people suffer from narcolepsy; it affects both men and women of any age.

6.1.5.2 Treatment

The goal in using medication is to approach normal alertness while minimizing side effects and disruptions to daily activities. Changes in behavior (such as the avoidance of caffeine, nicotine, and alcohol in the late afternoon or evening) combined with drug treatment have helped most persons with narcolepsy improve their alertness and enjoy an active lifestyle.

Common medications are stimulants to improve alertness and antidepressants to control cataplexy, hypnagogic hallucinations, and sleep paralysis. Some of the most common side effects of stimulants are headache, irritability, nervousness, insomnia, irregular heartbeat, and mood changes. Effects and side effects vary from one drug to another, which is why treatment should always be discussed with a specialized physician.
Together, a healthy physical routine, ongoing medical treatment, and sharing concerns can help to cope and live well with narcolepsy.

6.2 Bed Design Automation

When designing a bed, a lot of time, effort, and resources are spent to acquire data. The technique of data mining provides a return on this investment by combining expertise knowledge with raw data, allowing use of the collected data to its fullest. Data mining is the process of discovering meaningful new correlations, patterns, and trends by sifting through large amounts of data stored in repositories, using pattern recognition technologies, as well as statistical and mathematical techniques. Almost all data mining techniques involve using today’s increased computing power and advanced analytical techniques to discover useful relationships in large databases.

The most important application in the field of this work is to create a mathematical link between a subject (or a population class) and optimal sleep system characteristics in accordance with standardized LGA or CTBA properties. The goal is to use the system in a research environment to extract specific information easily and quickly.

The first subsection concentrates on neural networks that simulate the expert decision process by deciding which sleep system is optimal for a subject based on measurement output. The second subsection describes how a dynamic database is used to continually update information and generate a limited amount of straightforward output.

6.2.1 Mathematical Techniques: Neural Networks

In order to replace the expert decision process, a direct link has to be formed between a subject and his or her corresponding optimal sleep system. For example, a small part of the decision process is implemented in a neural network, considering only the criterion $P_8$ (see Chapter 5). The input matrix ($6\times20$) of the network consists of the anthropometrical data of a selection of 20 subjects (s1–s20), as illustrated in Table 6.1. The second measurement sequence (measuring five polyurethane mattresses, see Chapter 5) is used as training/test set.

<table>
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<th>TABLE 6.1 Input Matrix</th>
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<td>Sex (s1)</td>
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<td>Pelvic width (s1)</td>
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<th>TABLE 6.2 Output Matrix: First Option</th>
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<tr>
<td>Best Mattress # For s1</td>
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The output matrix has to determine the sleep system offering the best support qualities for each subject. There are several possibilities to represent the output; the first option shows the number of the best sleep system for each subject in a $1 \times 20$ matrix, as illustrated in Table 6.2.

A second possibility is to work with binary codes. The result is a $5 \times 20$ output matrix (illustrated in Table 6.3), each row specifying a mattress and each column indicating a subject. Code 1 identifies the best mattress (out of five) for a certain subject; code 0 is applied to the four remaining mattresses.

The main problem with the previous two types of output representation is that the neural network will have to produce interpolations. This might lead to major errors, as differences between two subsequent mattresses are significant (e.g., mattress # 3 having a firm pelvic zone and # 4 having a firm shoulder zone). The third option represents mattress characteristics in the output matrix instead of mattress numbers, so that interpolations can lead to only relatively minor errors. This results in a $4 \times 20$ output matrix (Table 6.4), each row representing one of the four mattress characteristics that were described in the previous chapter.

Only five subjects from the training set and two subjects from the test set were correctly connected to their optimal sleep system when using the first output matrix, so this possibility is not an option. In the case of a binary output code, the network is able to assimilate the training set information, but gets over-trained, and only connects three subjects from the test set.

### TABLE 6.3 Output Matrix: Second Option

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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 6.4 Output Matrix: Third Option

<table>
<thead>
<tr>
<th>Head CTBA value of best mattress # for s1</th>
<th>Head CTBA value of best mattress # for s2</th>
<th>…</th>
<th>Head CTBA value of best mattress # for s20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder CTBA value of best mattress # for s1</td>
<td>Shoulder CTBA value of best mattress # for s2</td>
<td>…</td>
<td>Shoulder CTBA value of best mattress # for s20</td>
</tr>
<tr>
<td>Waist CTBA value of best mattress # for s1</td>
<td>Waist CTBA value of best mattress # for s2</td>
<td>…</td>
<td>Waist CTBA value of best mattress # for s20</td>
</tr>
<tr>
<td>Pelvic CTBA value of best mattress # for s1</td>
<td>Pelvic CTBA value of best mattress # for s2</td>
<td>…</td>
<td>Pelvic CTBA value of best mattress # for s20</td>
</tr>
</tbody>
</table>
correctly, as illustrated in Figure 6.15. Also, the third option is not able (yet) to generate reliable results, which could be expected, as the amount of input-output information is not sufficient to train the network for this kind of relatively complex output characteristics.

Finally, only a limited number of polyurethane mattresses—which cannot be adjusted—were measured. Consequently, the best support mattress has to be chosen out of a limited number of systems, not necessarily coinciding with optimal back support. Training and test results will considerably improve when using flexible types of sleep systems (e.g., with the ability to adjust or optimize stiffness properties) like the ones that were measured in the third measurement sequence (see Chapter 5). These systems have the advantage that optimal settings can be measured, which yields a better correlation between anthropometries and optimal bed characteristics. These measurements, however, were not yet available for training/testing at the time neural networks were established.

FIGURE 6.15 Expected vs. simulated values.

FIGURE 6.16 Main control menu.
6.2.2 Graphical Techniques: User Interface

The core of the actual system is a Microsoft® Access® database (containing all records), to which Visual Basic® scripts are added for statistical calculations and for interfacing. The main control menu (see Figure 6.16) groups all major commands, including the ability to add new records for a subject or a sleep system, to modify records, and to generate output based on statistical calculations.

As for parameter input, several sheets are provided to add or to change records. When adding a sleep system, mechanical properties (e.g., CTBA core stiffness) are filled out for different zones (e.g., shoulder zone), as illustrated in Figure 6.17. Further, the type of sleep system (e.g., ADS® latex mattress) is specified, together with the different test series of which the sleep system is part.

When adding a subject, anthropometrical properties (e.g., shoulder width) are filled out, as illustrated in Figure 6.18, in order to make an estimation of body dimensions and weight distribution. Further, all measurement results are added (e.g., the optimal sleep system for a lateral sleep position) for all measurement sequences in which the subject participates.

All records mentioned can be adjusted or deleted interactively, as illustrated in Figure 6.19.

The main merit of the software is that it controls the mathematical link between anthropometrical properties and sleep system characteristics. A
FIGURE 6.18 Subject parameter input.

FIGURE 6.19 Parameter modification.
statistical multiple correlation is calculated, allowing the user to modify most parameters.

At first, a choice is made for which group of subjects or sleep systems a correlation is needed, as illustrated in Figure 6.20. This permits studying the influence of a specific spectrum of sleep systems (e.g., polyurethane mattresses) on a particular spectrum of subjects (e.g., women). The fact that measurements originating from different measurement sequences can be combined is a substantial advantage.

The selection procedures can easily be made interactively. Figure 6.21 depicts an example, selecting women between 20 and 30 years old with a weight between 50 and 60 kilograms. Further specific subject groups (e.g., back patients) can be selected.

Second, calculation parameters can be adjusted, as illustrated in Figure 6.22. For the system to calculate accurate multiple correlations between anthropometrical properties and sleep system characteristics, at least five anthropometrical

**FIGURE 6.20** Calculation group definition.

**FIGURE 6.21** Subject selection.
input parameters should be selected. When more parameters are picked, the system will calculate multiple correlations using the five most significant parameters. Calculation time—mostly less than a minute—is monitored interactively.

Further, a selection is made to define which characteristics of the sleep system have to be determined by the correlation. At this point only elasticity characteristics have been included (as this study is focusing on back support), but other parameters can easily be implemented at a later stage. Finally, the significance level—to which the resulting output has to be limited—and the name of the output sheet are chosen. Figure 6.23 illustrates an excerpt of an output sheet.

**FIGURE 6.22** Calculation parameters.

**FIGURE 6.23** Output sheet.
6.3 Bed Selection: Guidance Techniques

Shop assistants in a sleep system store are usually not familiar with the methodology, the numerical techniques, and the codes used in the previous section. The chance that people who are actually buying a sleep system are familiar with these procedures is even smaller. As a consequence, result interpretations should be automated and simplified in such a way that a nonexpert can understand them, without doing harm to the accuracy of the results. This section describes the potential use of automation techniques to overcome the problems of result interpretation and to represent the results in a comprehensible way. A few examples are given on how these techniques can be implemented as a marketing strategy or selling tool.

In general, two ways of working can be distinguished, depending on whether measurements (e.g., of spinal alignment) are actually taken in the store, or in a specialized lab.

In the latter, a large group of measurements is performed in optimal laboratory conditions on a large test group to form a statistical link between anthropometrical characteristics (e.g., body weight) and optimal sleep system characteristics (e.g., optimal spring stiffness in a pocket spring mattress). The measurements that are described in Chapter 5 could be taken as an example. The goal is to choose an optimal bed for a certain individual in the store, by connecting his or her anthropometrical characteristics to optimal sleep system characteristics. To do this, the individual in the store is matched to the people in the test group, and the conclusions for the people in the test group are applied to the individual. However, the individual is not linked to one single subject of the test group, but to the entire group by interpolation based on the individual’s anthropometrical characteristics. In other words, the person gets an individualized advice; no generalizations are made.

As a consequence, the conclusions that are drawn in the store stand or fall with the quality of the laboratory measurement. There are no significant problems as far as accuracy is concerned, but care should be taken not to draw conclusions based on extrapolations (e.g., when a choice is made for latex mattresses, it is dangerous to do this based on pocket spring measurements on a laboratory scale). Also, conclusions for a person weighting 100 kg cannot be made if the test group only consisted of people with a body weight lower than 90 kg. In other words, the laboratory test group (beds and people) should be consistent with the group in the store. Furthermore, the test group should also be large enough to get statistically significant correlations.

The advantage of this way of working is that a “virtual” choice is made, which means that the optimal bed can be chosen without the presupposed condition that is present in the shop system, which opens the possibility of offering a larger range of beds than what is actually available in the shop. This could even result in a completely virtual range of beds that could be offered through the Internet (see Section 6.3.4), but the weak point of this is that most people want to “look and feel” before buying a bed, even if this physical contact is not always (ergonomically) relevant.
TABLE 6.5 Personalized Advice

<table>
<thead>
<tr>
<th>Male Subjects</th>
<th>Large Shoulders</th>
<th>No Large Shoulders</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight &lt;X kg</td>
<td>Mattress E/Support D</td>
<td>Mattress D/Support B</td>
</tr>
<tr>
<td>Body weight between X and Y kg</td>
<td>Mattress A/Support A</td>
<td>Mattress A/Support E</td>
</tr>
<tr>
<td>Body weight &gt;Y kg</td>
<td>Mattress C/Support B</td>
<td>Mattress C/Support D</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Female Subjects</th>
<th>Small Waist</th>
<th>No Small Waist</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body weight &lt;X kg</td>
<td>Mattress C/Support E</td>
<td>Mattress D/Support C</td>
</tr>
<tr>
<td>Body weight between X and Y kg</td>
<td>Mattress D/Support A</td>
<td>Mattress A/Support B</td>
</tr>
<tr>
<td>Body weight &gt;Y kg</td>
<td>Mattress A/Support B</td>
<td>Mattress C/Support B</td>
</tr>
</tbody>
</table>

Furthermore, this way of working also depends on the information that is acquired in the store. Both personal information (e.g., preference of sleeping soft, sleep disorders, sweating, etc.), as well as anthropometrical information (e.g., body length), can be important. The more data that are available, the more accurately a bed selection can be made. When looking at the low-end market, for example, the introduction of a small table based on laboratory measurements (see Table 6.5 for an imaginary example) would be relatively simple to establish and a large step forward.

A second way of working is to perform all measurements in the store and, thus, is more straightforward. The advantage is that data are directly related to the individual and to the sleep system that is measured, and no interpolation is made (which could inhibit inaccuracies, e.g., inconsistent laboratory test groups; see Section 6.2.1). The disadvantage is that it is difficult to copy lab conditions in a store, because expensive equipment is needed, an expert is required to perform the measurement, and measurement conditions are not always the same (e.g., less time is available), especially in the low-end market. Another disadvantage is that only the range of beds available in the store can actually be measured.

The optimal sleep system guide would combine the advantages of both ways of working described above, by performing measurements in the store (e.g., spinal alignment) and using additional information from lab measurements under specific conditions, but the most important aspect missing at present is the awareness of the customer. It will probably take some years before customers will be willing to take some time and effort (e.g., be measured) before buying a new sleep system, especially if no problems (e.g., low back pain) have risen yet.

Below several examples of customer advice systems are given, based on in-store and laboratory measurements. These systems may not always be perfect. They are a first step toward individualized and objective sleep system advice, which is important because “test-lying” in a store is often not relevant, because it is influenced too much by subjective parameters.

First, subjective parameters do play a role, but it is dangerous to rely on a first impression for several reasons. At first, different parameters play a role: when lying down for a few minutes a relaxed position may give the impression that the sleep system gives a good support while this is often not the case. For example, when lying down on a
mattress that is too soft, some muscles in the abdomen region are relaxed (which gives an impression of comfort) but the spine is not supported as it should be.

Second, a person’s sleep position is always dependent on the sleep system he or she is used to sleeping on. It always takes several weeks (3 to 6) to get used to a new bed. As a result, it is possible that a person who is used to sleeping on an unsatisfactory bed (and with a sleeping posture that is adjusted to this bed) will feel discomfort when sleeping on a new bed, even if this new one is better.

### 6.3.1 Spinal Alignment

Two types of systems are described below: the first one focuses on mattress properties, the second one on base settings. The first system gives the customer advice based on laboratory measurements of a relevant test group (test subjects and mattresses are consistent with the group aimed at in the store; spinal alignment is measured in the lab). A statistical link between anthropometrical characteristics and optimal sleep system characteristics is formed in the store for an individual based on measurements of body weight, body length, and body width at different locations (pelvis, waist and shoulder). For these measurements it is necessary to set up dedicated and easy-to-use equipment in the store. Based on the advice, dedicated software is needed to help the shop assistant compose an individualized sleep system (e.g., combining polyurethane blocks with different material properties). For example, Lattoflex® uses this technology for their Winx Uniq® range of sleep systems (see Figure 6.24, in Dutch).

A second possibility is to focus on base settings to optimize spinal alignment, such as by adjusting slat height in different body zones. To obtain this, forces that act on different slats are measured in the store and are (nonlinearly) related to spinal alignment measurements that are carried out beforehand on a test group under laboratory conditions. The Ergosleep® system (commercialized by sleepy®) adjusts slat height to three different levels (see Figure 6.25) based on computerized force measurements.

### 6.3.2 Pressure Distribution

Most customer advice systems currently available make use of in-store pressure interface mattresses (see Section 1.1.2) in order to perform an in-store measurement of body weight distribution on a sleep system. The goal is to select the system with the best performance (i.e., best pressure distribution).
However, when concentrating on normal healthy people, back support qualities are of primary importance. Only in the case of hospital applications (where people are forced in a recumbent position for a longer time) do pressure relief and body weight distribution become of primary importance. Furthermore, there is no coupled relation between pressure relief and spinal alignment, which means that pressure interface measurement does not provide information on spinal alignment.

Measurements originating from a pressure mattress (measuring body weight distribution) nevertheless can be applied in relation to body support during sleep, as long as an expert interprets the measurement results and no coupled relation between pressure relief and spinal alignment is made for the entire body. In this case, the information provided by the system is not relevant on its own but rather complementary to the expertise of the sales assistant. There are many systems on the market to carry out pressure
distribution measurements on a sleep system; one of these is the Xsensor® pressure mapping system by Roho® (see Figure 6.26).

6.3.3 Muscle Relaxation

A limited number of customer advice systems make use of in-store EMG measurements. The goal is to detect the electrical signals associated with muscle contraction (see Section 3.1.2.4.1) and to select the system with the best performance (i.e., best pressure distribution). Although muscle relaxation is an important factor during sleep, there is no scientific evidence that there is a coupled relation between muscle activity minimization and body support optimization (and spinal alignment). By measuring and analyzing EMG signals on different sleep systems, some additional information is provided on the condition of the human body, but no prediction can be made regarding which system offers the best support qualities, unless spinal alignment itself is evaluated. EMG measurements, therefore, are not relevant on their own, but nevertheless can be useful, as long as an expert interprets the measurement results and no coupled relation between EMG and spinal alignment is made. For example, the Back-Up® measuring system uses this technology (see Figure 6.27).

6.3.4 Web-Based Customer Advice

In order to assist customers at home, a Web-based interface can be developed depending on the target group. The main advantage of using the Internet is
to avoid problems with software installation and updating—only a web browser is needed locally—and to establish a central database containing customer information that is fed back to the data mining system and the distribution process (e.g., product mix information). If required, the system also can be extended to e-commerce purposes. An example of this type of interface (see Figure 6.28, in Dutch) allows the user to choose a sleep system that matches his or her individual needs.
6.4 Conclusion

The first section of this chapter condensed the results of the previous chapters into a set of practical guidelines that can be used by both bed designers and customers. Along with general guidelines relating to physical, physiological, and psychological factors, emphasis was put on the prevention of low back pain and recovery from it.

The second section of this chapter described the possibility of automating the described procedures (see Chapters 3 to 5) to overcome the problems of result processing. An attempt is made to replace the expert decision process by neural networks and to automate most procedures. The resulting dynamic database is able to continually update all information and to generate a limited amount of straightforward output.

The third section described how advice can be given in a shop, and how results can be represented in a comprehensible way so that they can be implemented as a marketing strategy or selling tool (e.g., to facilitate and improve the selection of the best possible bed).

The main future objective is the implementation of more parameters (e.g., pressure distribution on a mattress) to give an overall view of the quality of an existing sleep system or to assess new concepts of design. Thanks to the open structure of the existing system, options can be added easily, and derived systems for specific purposes can be developed for a particular population (e.g., people with back disorders), for a specific type of shop (e.g., a simplified version for wholesale businesses), for an explicit type of sleep system (e.g., pocket spring mattresses), or for a precise objective (optimization of back support).

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Conclusion

Summary

In an effort to brighten up the twilight zone surrounding statements and commonly accepted propositions about the ergonomics of sleeping, this study objectively selected the most important ergonomic factors affecting this issue, including physical, physiological, and psychological factors. When concentrating on normal healthy people and the prevention of eventual disorders, back support qualities are of primary importance; the optimal sleep system (i.e., the combination of a mattress, a bed base, and a pillow) has to support the human spine so that it adopts its natural position. Mechanical properties (e.g., mattress elasticity) need to be optimized however, within the limitations posed by nonmechanical preconditions (e.g., high perspiration of an individual). For applications involving injured people, other issues come first (e.g., pressure-relieving qualities are of prime importance for hospital applications).

Second, the underlying determinants of these ergonomic properties were discussed, including the direct influence of different types of body support and postures. Most sleep systems, however, force a subject into a certain sleep position, thus indirectly influencing spinal alignment as well. Consequently, the design of sleep systems (correctly assigned to different population classes) is of primary importance.

The expertise cited above—originating from both literature and know-how—is needed to determine the right sleep system for each individual. It establishes a strong input base for further investigations, as illustrated on the flowchart in Figure 7.1.

Measurements evaluating spinal alignment during bed rest—by comparing the spine position on a sleep system with the spine position during upright standing—are an important part of this definition process. Different measurement techniques were analyzed and compared. Based on this assessment, it was possible to decide which equipment was most suitable for measurements of the vertebral column. At a first stage, a two-dimensional technique was conceived, but as people are not two-dimensional, white-light raster line triangulation hardware and active contour software were successfully applied in three-dimensions to the evaluation of the spine. The main advantages of this equipment are (1) the person is not subjected to harmful radiation; (2)
Optimization process of sleep system determination. It has a low measurement and computation time; and (3) no contact with the measured surface is required.

Further, it was explained how these measurements fit into a comprehensive methodology to gain clear insight into the impact of bed design on spine support—especially in relation to anthropometrical properties. Starting from guidelines generated by simplified measurements, the influence of different types of body support on spine support was studied in depth through detailed measurements, while gradually focusing on the relation with anthropometrical properties. Whereas in the beginning of the measurements only predetermined systems were used, adjustable systems were measured at a later stage. The acquired knowledge at the end of each stage enabled the performance of more complex measurements in the next stage.

The first measurement stage gave general guidelines on the influence of a firmer or softer mattress core on the shape and position of the vertebral column. The most significant outcome was the difference between male and female subjects, and the fact that male subjects with an athletic body build and female subjects with a pronounced body contour are not sufficiently supported by sleep systems with homogeneous stiffness.

The second measurement stage studied the response of the vertebral column of different population groups to different kinds of mattresses and bed bases, especially when sleep systems are subdivided into several zones in the cranio-caudal direction, each having different local material properties. The outcome was a multiple correlation between the body build of a subject and the type of zones of which a supportive mattress should consist.

The third and last measurement stage’s goal was zone quantification; it defined which stiffness values had to be applied to each zone, depending on anthropometrical properties, giving a clear insight into the underlying relationships. Female subjects, however, required the implementation of a larger number of measurements.

Consequently, how measurements can be simulated in order to reduce—or even avoid—the elaborate procedures that go together with measurements was discussed. Four different simulation techniques were discussed: graphic modeling, straightforward numerical modeling, finite element modeling, and neural networking.

Graphic modeling (using multibody dynamics) of a subject on a sleep system was successful, as it was able to visualize the support qualities of a certain sleep system for a subject in an accurate and parameterized manner. The only minus point was the calculation time, which explains the need for (nongraphic) linear numerical simulation techniques for real-time applications. Considerable simplifications were made, giving rise to models unable to provide an exact prediction of the behavior of the vertebral column.
on a sleep system. Sufficient accuracy, however, was obtained to trace differences between sleep systems. These models can be used to make a prompt but truthful decision about the degree of suitability of a sleep system for a subject.

Finite element models were considerably simplified, but not accurate enough to obtain an exact match between simulations and measurements. On the other hand, there is a strong indication that finite element models (probably in combination with multibody dynamics) will be able to provide accurately predict the behavior of the vertebral column on a sleep system. The use of neural networks for measurement simulation was not successful, because not enough measurement data were available to train the network.

Finally, the potential for using automation techniques to overcome the problems of result processing (which is extremely time consuming) and result interpretation (which is difficult for a nonexpert) was discussed, and specific recommendations were made (e.g., for people with back pain). Neural networks could replace the expert decision process, but again more measurements were needed to feed the network. Straightforward statistical procedures—in combination with future developments of neural networks—were the basis for a data mining system that was able to automate all calculation procedures and to represent the results in a comprehensible way. The dynamic database is able to continually update information and to generate a limited amount of straightforward output, which can be easily implemented as a marketing strategy or selling tool. One example of a practical implementation of the database is a Web-based client advice system.

The most important advantage of the described technology is the integration of constituting units, of which some are already in use in both research and selling environments.

Innovations

Although many things have been said and written about the physical quality of sleep, it is disturbing to find how few of these communications are founded on actual research. This study succeeds in brightening up (at least a part of) the twilight zone surrounding statements and commonly accepted propositions about this issue.

While establishing a scientific foundation for physical aspects of sleeping, this book’s goal is to create a new and hybrid discipline at the crossing of engineering and medicine, with elements of mechanics, physical therapy, mathematics, orthopedics, and physics. In this framework, the following milestones were developed.

• New parameters were defined (1) to characterize the anthropometrical properties of a person in relation to sleeping, (2) to typify a sleep system, and (3) to evaluate the physical quality of sleep. For this evaluation, several aspects of sleep were defined and combined, and characterizing parameters were identified for each of these aspects. Among other elements, ergonomic factors were objectively selected and defined, including both mechanical (e.g., spine support) and nonmechanical constituents (e.g., temperature).
• Adequate measurement equipment was developed to evaluate the shape of the vertebral column when lying on a sleep system. White-light raster line triangulation hardware and active contour software were successfully applied in three dimensions to the
measurement and analysis of the spine. The main advantages of this new measurement system are that the person is not subjected to harmful radiation, it has a low measurement and computation time, and no contact with the measured surface is required.

- The feasibility of replacing or completing elaborate experimental work by simulations was demonstrated.
- Based on measurements—and partially on simulations—progressively clearer insight was gained into the impact of bed design on spine support, especially in relation to anthropometrical properties.
- Specific sleep guidelines were included for people with specific types of complaints, such as low back pain.
- Automation techniques were developed to overcome the problems of result processing (which is extremely time consuming) and result interpretation (which is difficult for a nonexpert). The resulting dynamic database is able to continually update information and generate a limited amount of straightforward output, which can be easily implemented as a marketing strategy or selling tool. One novel example of the practical implementation of the database is a Web-based client advice system.

Future Work

The acquired expertise establishes a basis for further investigations, both inside and outside the scope of the current study, and hopes to begin a dialogue on this issue.

- The design of sleep systems (and the correct assignment to different population classes) is of primary importance at present. Efforts should be made to achieve perfect sleep conditions in the future by enlarging the span of the current study, especially regarding the influence of the mental quality of sleep and its relation to physical factors. Adequate parameters should be defined to characterize these aspects.
- The existing measurement equipment is able to evaluate the shape of the spine when lying on a sleep system. Care, however, should be taken in enlarging the robustness of the system and decreasing its sensitivity to environmental factors.
- Partly due to the limited nature of the research carried out in this field, simulations have failed so far to replace or complete elaborate experimental work. However, its feasibility was demonstrated, and the most challenging requests for future work come from here.
- Finally, the research carried out in this work resulted in a database system that is able to translate insight into the impact of bed design on spine support (especially in relation to anthropometrical properties) to usable guidelines. The main disadvantage of the present system is its limitation to normal, healthy people. An important task for the future is to add specific target groups (e.g., patients with cardiovascular problems), and to concentrate on the relation with specific parameters (i.e., age). For example, both children and elderly people need specific recommendations.

Certainly, this list of possible extensions is incomplete. It will be a future challenge to reveal other application domains and to discover the full extent of sleeping.
Final Word

When I first started to study sleep, it seemed there was not much left to discover. However, commonly accepted knowledge soon appeared to be a façade, and contesting it was not an easy task. But now that people have become more aware of the importance of sleep, this work has become very rewarding.

So fighting windmills does make sense.

It also appears that Don Quixote himself suffered from several sleep disorders such as insomnia, sleep deprivation, and disruptive loud snoring (Cervantes, 1990; Iranzo et al. 2004).

I dare to say that we have done each other a good turn.

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